NOAA Technical Memorandum NOS CS 35

CHART ADEQUACY EVALUATION OVER THE COASTAL WATER OF HAITI USING SATELLITE-DERIVED BATHYMETRY

Silver Spring, Maryland
January 2016

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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ABSTRACT

As part of the humanitarian aid and as a response to the Haiti Earthquake disaster, the National Oceanic and Atmospheric Administration (NOAA) and other hydrographic offices around the world have provided support to SHOH (Service Hydrographique et Océanographique de Haiti) by training SHOH personnel, surveying key areas around Haiti and updating the charts. As part of the 2013 NOAA effort to support SHOH, a novel approach was used to evaluate shallow-waters in areas that were not surveyed in 2010. Commercial multispectral satellite imagery (Landsat 8 and Worldview 2) was used to derive bathymetry. This report reviews the satellite-derived bathymetry procedure and the results produced over the coastal waters of Haiti. The procedure was conducted using Geographic Information System (GIS) software (ArcMap 10.1). A step-by-step procedure is provided in the GEBCO Cook Book and in the Appendix of this report.

Key Words: Satellite-derived bathymetry, Haiti, Hydrography, Nearshore bathymetry, Geographic Information Systems (GIS), Chart adequacy

1. INTRODUCTION

In January 12, 2010, a magnitude 7 earthquake occurred with an epicenter approximately 25 kilometers (16 mi) west of Port-au-Prince, Haiti's capital. In addition, at least 52 aftershocks measuring 4.5 or greater had been recorded by January 24, 2010. Death toll estimates ranged from 100,000 to 159,000. The earthquake caused major damage in Port-au-Prince, Jacmel and other settlements in the region. Many notable landmark buildings were significantly damaged or destroyed, including the Presidential Palace, the National Assembly building, the Port-au-Prince Cathedral, and the main jail.

Following President Obama’s pledge of support relief efforts in Haiti and at the request of the U.S. Coast Guard, NOAA sent a multi-tiered disaster response team to Haiti to conduct emergency maritime surveys and damage assessment imagery of key Haitian ports to ensure that waterways were safe for navigation and the transport of relief supplies. The U.S. survey effort was a collaborative effort between the U.S. Navy, U.S. Army, U.S. Coast Guard, National Geospatial-Intelligence Agency (NGA), and NOAA. Most of the hydrographic surveys were conducted in Port-au-Prince and near Cap Haitien. However, the depths for many of the surveys were in waters deeper than 10 m, several kilometers away from the shoreline.

A special meeting was held at the 12th Meso American and Caribbean Sea Hydrographic Commission (MACHC) meeting, Basseterre, Saint Kitts and Nevis (5-9 December2011), which addressed results of a Haiti Training course and Haiti Donors meeting that took place within the previous year. These activities were routed through MACHC Capacity Planning and highlighted the need for continued support. This technical memorandum reviews the 2013 NOAA effort to support SHOH in its hydrographic capacity. NOAA's Office of Coast Survey (OCS), Marine Chart Division (MCD) in collaboration with the Joint Hydrographic Center (JHC), University of New Hampshire have developed a GIS procedure that can be used as a tool to evaluate the adequacy of the charts around Haiti and can be used by SHOH for further investigation of their charts. The procedure was developed using GIS software (ArcMap 10.1) and commercial multispectral satellite imagery (Landsat 8 and Worldview 2) which was used to derive bathymetry. The NGA charts were evaluated as the most recent up-to-date charts that are available around Haiti (Figure 1). Key steps in the satellite-derived procedures include: (1) Pre-processing, (2) Water separation, (3) Spatial filtering, (4) Glint/cloud correction, (5) Applying the bathymetry algorithm, (6) Identifying the extinction depth, and (7) Vertical referencing.

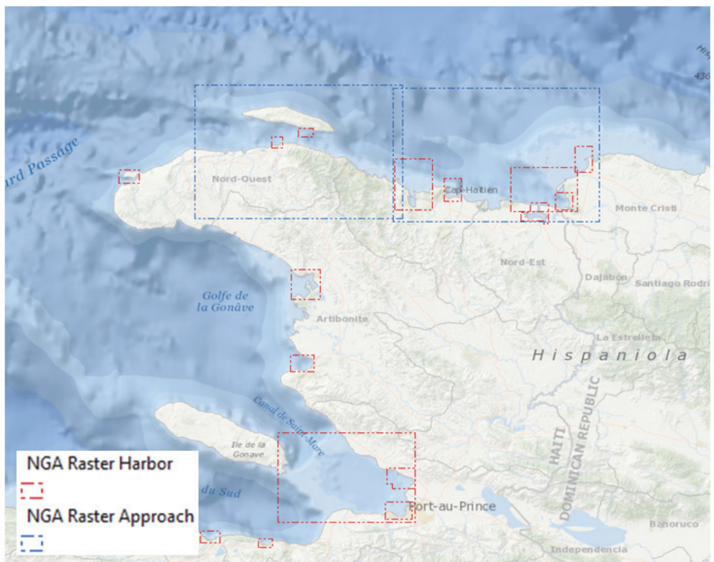


Figure 1. Coverage map containing the footprint of large and medium scale (> 1:200,000) NGA charts around Haiti.

2. MOTIVATION

Economic challenges exist in governments around the world, creating a need to make informed decisions with diminished funding. The motivation of this work is to utilize remote sensing resources as reconnaissance tools to identify changes between the current nearshore bathymetry and the depths marked on the chart.

As commercial satellite imagery is available for NOAA's use with minimal cost, it can provide excellent potential as an inexpensive tool for analysis. It avoids costs for transportation, establishment of GPS and tide stations, acoustic surveying and processing of the data. Without this option, NOAA might not be able to support SHOH with updates or tools for assistance.

3. SATELLITE-DERIVED BATHYETRY

The ability to derive bathymetry from multispectral satellite imagery is a topic that has received considerable research attention since the 1970s. Typical multispectral satellite platforms (e.g., Landsat, Ikonos, SPOT, and WorldView) collect data in multiple spectral bands that capture a broad spectral range (40 to 150 nm). Collectively, these bands typically span the visible to infrared portions of the electromagnetic spectrum. The physical concept underlying the ability to estimate bathymetry from multispectral imagery is the wavelength-dependent attenuation of light in the water column. To date, numerous algorithms for bathymetry retrieval have been developed. Satellite-derived bathymetry (SDB) utilizes these algorithms and procedures for operational survey planning for hydrographic offices.

Although the accuracy of SDB does not meet current International Hydrographic Organization (IHO) S-44 standards, results from this technique suggest that SDB can be a useful tool for survey planning and prioritization, especially for national hydrographic offices with limited resources. However, this application has two main requirements: 1) the data must be referenced to a chart datum (typically a tidal datum), and 2) the procedures must be based on readily-available, low-cost data and software.

The key steps in the satellite-derived procedure include:

1. **Pre-processing**– Satellite imagery is downloaded based on geographic location and environmental conditions (e.g., cloud coverage and sun glint).

2. **Water separation**– Dry land and most of the clouds are removed.

3. **Spatial filtering**– ‘Speckle noise’ in the Landsat imagery is removed using spatial filtering.

4. **Glint/cloud correction**– The Hedley et al. (2005) algorithm is used to correct radiometric contributions from sun glint and low clouds.

5. **Applying the bathymetry algorithm**– The bathymetry is calculated using the Stumpf et al. (2003) algorithm on the blue and green bands.

6. **Identifying the extinction depth**– The optic depth limit for inferring bathymetry (also known as, the extinction depth) is calculated.

7. **Vertical referencing**– A statistical analysis between the algorithm values to the chart soundings reference the Digital Elevation Model (DEM) to the chart datum.

4. DATA

4.1. Multispectral Satellite Imagery

The ability of light to penetrate the water provides the fundamental principle for inferring water depth using satellite remote sensing technology. The radiation reflected from the seafloor or the water column is captured by the sensor in the satellite platform using photo-detectors. A typical multi-spectral sensor contains several detectors, where each detector can capture a broad spectral range (70 to 150 nm) from the visible to the infrared portions of the electromagnetic spectrum.

Light transmittance through the water column varies as a function of wavelength. The spectral range of the sunlight that is able to penetrate seawater to appreciable depths is typically between 350 nm (ultraviolet-blue) to 700 nm (red), depending on the water clarity and the water depth (Jerlov 1976, Mobley 2004). Sunlight at wavelengths greater than 700 nm (infrared) has very low transmittance in seawater. Typically, satellite channels in the near-infrared ranges (800 to 900 nm) are used to delineate land/water boundary in coastal environments (Robinson, 2004).

The solar radiant energy that is able to penetrate the water surface decays through the water column is an exponential function of the diffuse attenuation function, K(λ) ,and depth, z (Jerlov 1976, Mobley 2004). The observed radiance in shallow waters can be expressed as (Philpot 1989, Maritorena et al. 1994):

$$L_{obs} = L_b e^{-2K(\lambda)\cdot z} + L_w \quad (1)$$

where L_{obs} is the radiance observed at the sensor's detector, L_b is the radiance contribution from the bottom, and L_w is the observed radiance over optically deep water with no bottom contribution. As a result, only a subset of the spectral range from the downwelling irradiance reaches the bottom and is reflected back.

Landsat 8

The Operational Land Imager (OLI) aboard Landsat 8 has been operational since mid-2013. Current and historical Landsat satellite imagery provides a free and publically available resource. Satellite imagery is collected and archived by National Aeronautics and Space Administration (NASA) and U.S. Geological Survey (USGS). The swath width of Landsat 8 imagery is 185 km and its image resolution is about 30 m. Each image contains 8 bands at different spectral ranges (Table 1). The spectral range of the bands is from 0.430 to 1.380 µm.

Figure 2. Image of Landsat 8 satellite (USGS, 2013).

Table 1. Band names and wavelength ranges of the visible to shortwave-infrared multispectral Landsat 8 bands (USGS, 2013).

Band number	Band Name	Wavelength
Band 1	Coastal	0.430 - 0.450 µm
Band 2	Blue	0.450 - 0.510µm
Band 3	Green	0.530 - 0.590µm
Band 4	Red	0.640 - 0.670µm
Band 5	Near-IR	0.850 - 0.880µm
Band 6	Short wave -IR1	1.570 - 1.650µm
Band 7	Short wave-IR2	2.110 - 2.290 µm
Band 8	Cirrus (IR)	1.360 - 1.380µm

WorldView 2

DigitalGlobe's WorldView-2 (WV-2) imagery provides eight multispectral bands at a resolution of about 2 m (Table 2). The spectral range of the bands is from 0.400 to 1.040 µm. According to DigitalGolbe (2012), each band is dedicated to a particular part of the electromagnetic spectrum to be sensitive to a specific type of feature on land, above or beneath water bodies, and in the atmospheric column. Although the swath width of WV-2 (18 km) is much smaller than the swath width of Landsat imagery (185 km), the WV-2 image resolution (~2m) provides the ability to identify smaller features that cannot be observed in the Landsat imagery (~30 m pixel resolution).

Figure 3. Image of WV-2 satellite (DigitalGlobe, 2013).

Table 2. Band names and wavelength ranges of the multispectral WV-2 bands (Digital Globe, 2012).

Band number	Band Name	Wavelength
Band 1	Coastal	0.400 - 0.450 µm
Band 2	Blue	0.450 - 0.510 µm
Band 3	Green	0.510 - 0.580 µm
Band 4	Yellow	0.585 - 0.625 µm
Band 5	Red	0.630 - 0.690 µm
Band 6	Red Edge	0.705 – 0.745 µm
Band 7	Near-IR2	0.770 – 0.895 µm
Band 8	Near-IR2	0.860 – 1.040 µm

4.2. NGA Raster and Electronic Charts

U.S. chart production outside of its territorial waters is done by NGA, including the nautical charts within coastal waters of Haiti. The raster, or lithographic, charts produced by NGA contain survey information typically collected by the U.S. Navy. These raster charts are updated to reflect the latest available information to promote the safe navigation of maritime traffic.

In addition to the NGA raster charts, ENCs (Electronic Navigation Chart) are beginning to be produced. ENCs are vector data sets that conform to the International Hydrographic Organization (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification, and are provided with incremental updates that supply Notice to Mariners corrections and other critical changes. ENC data may be used to fuel Electronic Chart and Display Information Systems (ECDIS) (NOAA, 2013).

NGA released its first four ENCs in S-57 format for the Panama Canal and approaches on 01 OCT 2013. These ENCs will continue to be maintained by NGA with new source information from both the U.S. and Panama as it becomes available. Additionally, NGA is working to expand its ENC Portfolio within the MACHC Region in areas where the U.S. is the Prime Charting Authority (NGA, 2013). Currently, NGA has six ENCs in production in the coastal waters of Haiti.

5. METHODOLOGY AND RESEARCH APPROACH

5.1. Study Sites

Two study sites were used: (1) Port Au Prince as a control site to evaluate the SDB procedure (Figure 4) and (2) Baie de l'Acul that was used to evaluate the NGA charts (Figure 5). The decision for the control site was based on the recent (2010) hydrographic survey conducted by the U.S Navy (Figure 6). The evaluation site was also chosen based on the source diagram (Figure 7), which indicated that the last hydrographic survey conducted in the near shore waters of Baie de l'Acul was 1916.

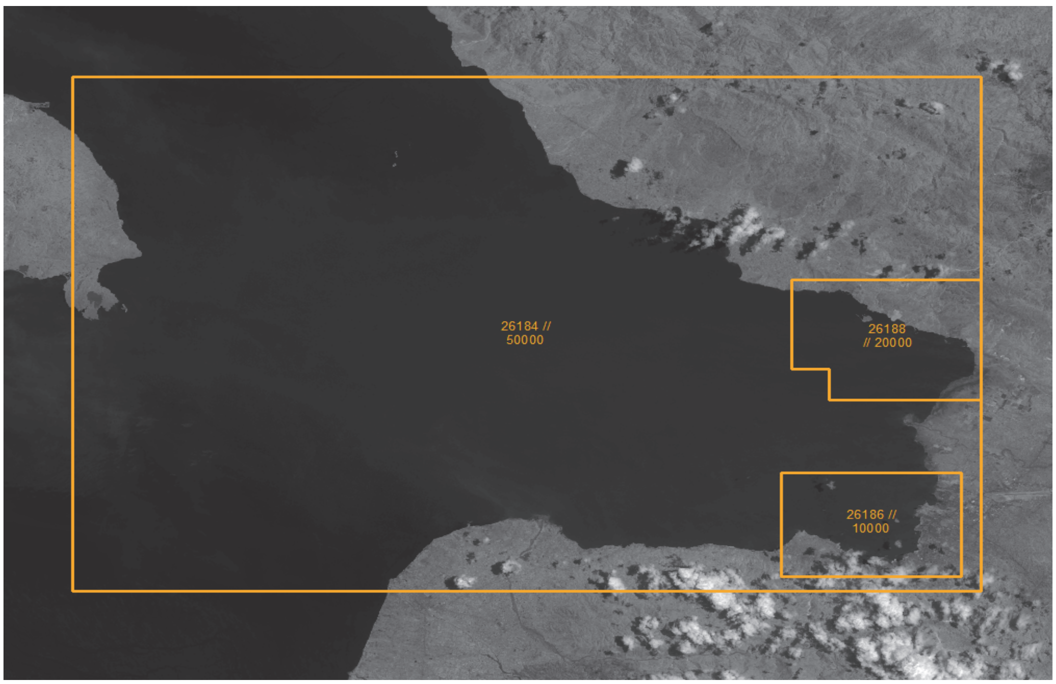


Figure 4. NGA map coverage contours of Port-au-Prince area overlaid on a Landsat 8 imagery (IR band).

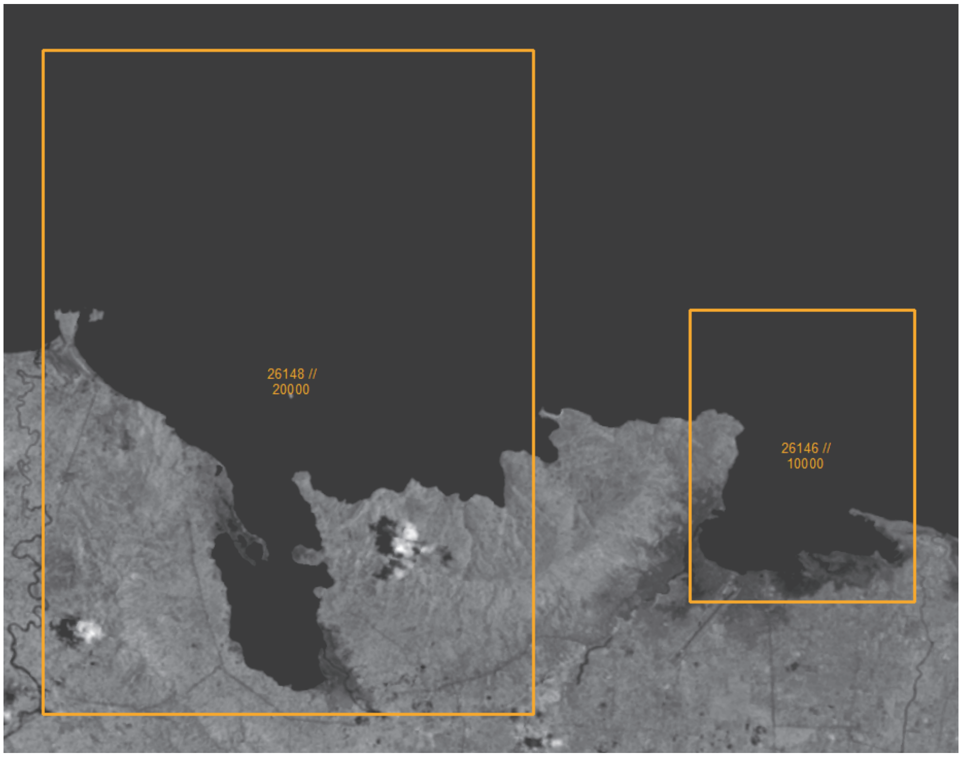


Figure 5. NGA map coverage contours of Baie de l'Aculthat area overlaid on a Landsat 8 imagery (IR band).

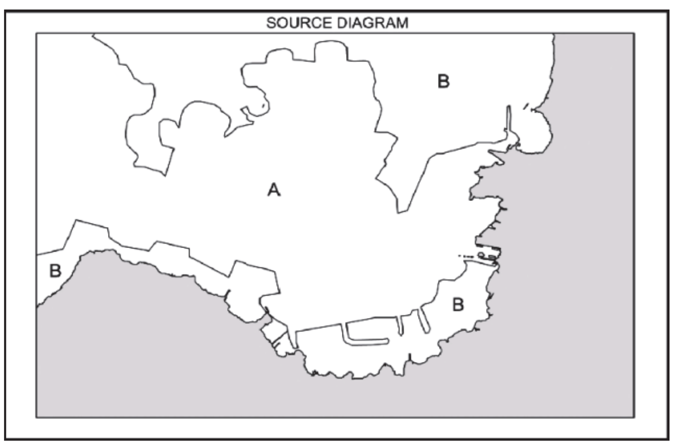


Figure 6. Source diagram of NGA Chart 26186: (Area A) U.S. Navy Survey from 2010 (Survey scale 1:1,000), (Area B) U.S. Navy Survey from 1978 (Survey scale 1:5,000 - 1:10,000).

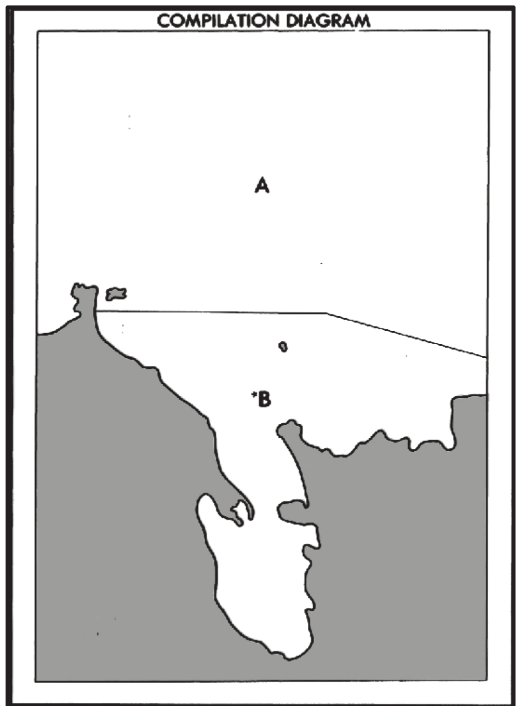


Figure 7. Source diagram of NGA Chart 26148: (Area A) U.S. Navy Survey from 1982 (Survey scale 1:25,000), (Area B) U.S. Navy Survey from 1915-16 (Miscellaneous data).

Table 3. NGA charts used in the study.

Study Site	Chart Name	Chart Number	Scale
Baie de l'Acul	Baie de l'Acul and Approaches	26148	1:20,000
Baie de l'Acul	Cap-Haitien	26146	1:10,000
Baie de l'Acul	Approaches to Cap-Haitien and Bahia de Monte Cristi	26142	1:75,000
Port-au-Prince	Port-au-Prince	26186	1:10,000
Port-au-Prince	Approach to Port-au-Prince	26184	1:50,000

5.2. Procedure Outline

5.2.1. Downloading Datasets

Based on the charts geographic location, a search was conducted in the USGS archives (http://earthexplorer.usgs.gov/) for available Landsat 8 imagery. Using a 'quicklook view' mode (i.e., low-resolution imagery) to review the different scenes (Figure 8), only images with minimum cloud coverage (0% to 10 %) and very little sun glint were chosen. These images were downloaded from the website into the ArcMap project, where the bands of the image were stored separately in a TIF format.

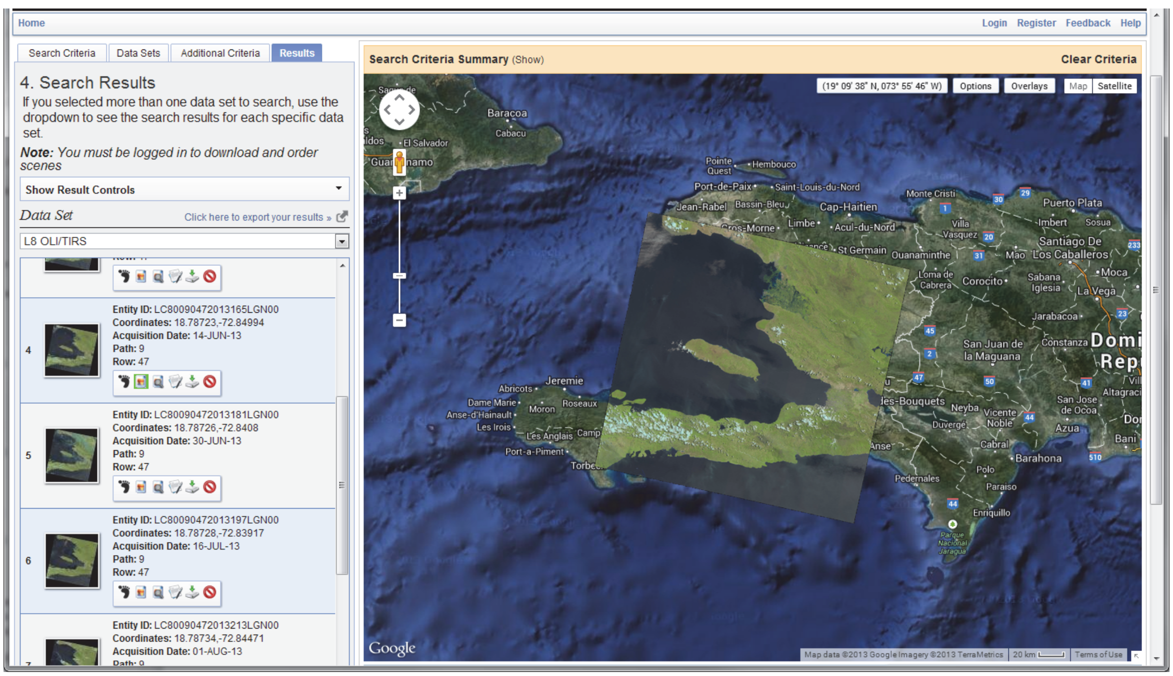


Figure 8. Screen capture for Landsat 8 imagery search using the USGS website.

Similarly, an inquiry for WV-2 imagery based on the geographic location was conducted in the NGA archives (WARP). The portal also allows the user to review the different scenes (Figure

9). Only multispectral images with minimum cloud coverage (0% to 10 %) and very little sun glint were chosen. These images were downloaded in a National Imagery Transmission Format (NITF) file format from the NGA website into the ArcMap project and converted locally into a TIF format.

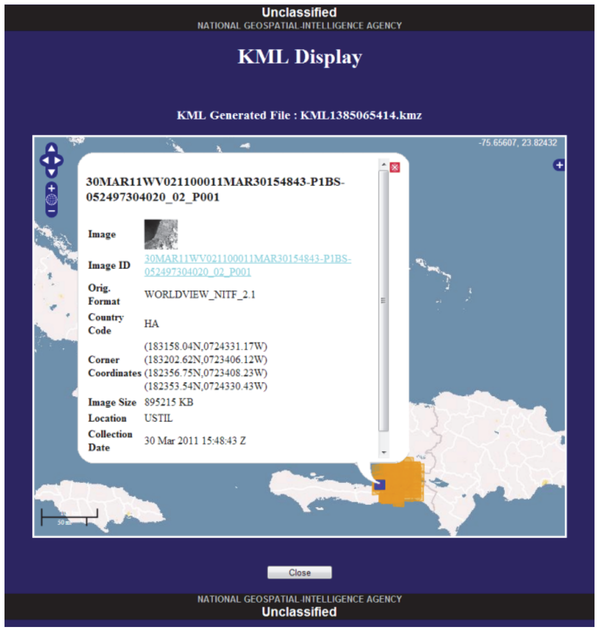


Figure 9. Screen capture for WV-2 imagery search using the NGA website.

Appendix A.1 provides step by step how to download the Landsat 8 or WV-2 imagery.

5.2.2. Horizontal Referencing of the Imagery to the Chart

Although the archive state of the satellite imagery datasets (Landsat 8 and WV-2) are georeferenced, there was a noticeable observed horizontal offset ranging up to 20m in the WV-2 imagery. The satellite imagery was referenced to the chart based on the chart graticules. Although the cause of the horizontal offset could be uncertainty from both the imagery and the chart, the goal is to evaluate the chart. Accordingly, the chart provides the reference datum, both horizontally and vertically.

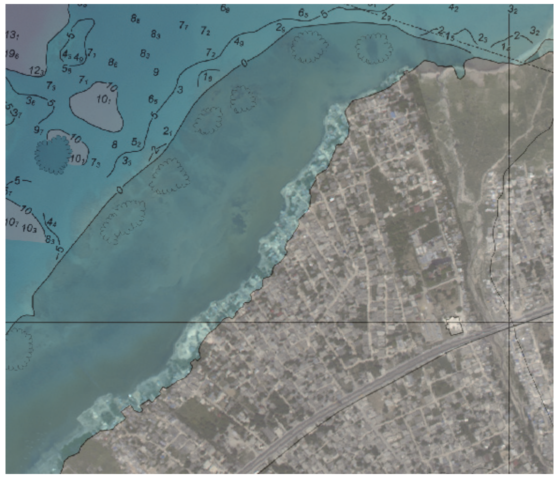


Figure 10. Figure showing the misalignment between WV-2 and the chart.

Appendix A.4 provides step by step procedure in ArcMap to horizontally reference the satellite imagery to chart datum.

5.2.3. Spatial Filtering

A radiometric noise is noticeable in both the Landsat 8 and the WV-2 imagery. This radiometric issue is call "striping" and occurs when detectors go out of radiometric adjustment (Figure 11). In the satellite-derived bathymetry case, a detector might record spectral measurements over a dark deep body of water that are almost uniformly greater brightness values than other detectors for the same band. The result would be an image with noticeable lines that are brighter than adjacent lines. An additional radiometric noise that might be present is 'speckle noise' (random brightness changes throughout the image). The cause of the speckle is unclear and may be related to memory effects, scan-correlated shift and coherent noise (Vogelmann et al. 2001). Spatial filters can be applied as a radiometric correction. An additional procedure for the removal of the striping is applied during the sun glint removal (section 2.5.5).

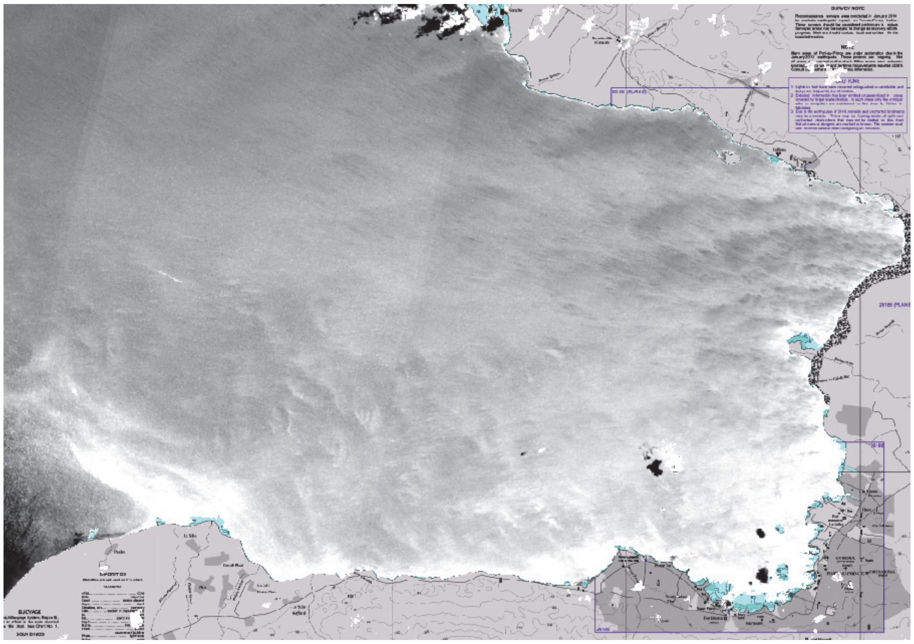
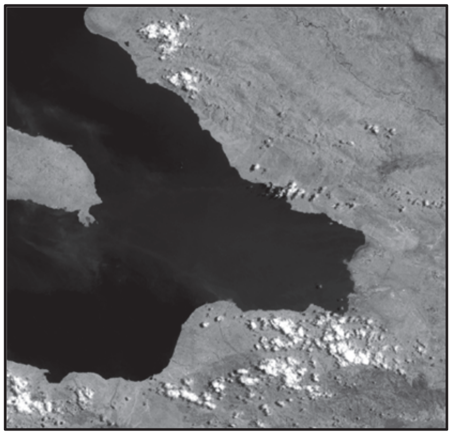


Figure 11. Figure showing the striping in Landsat 8 and the chart.

Appendix A.5 provides step by step procedure in ArcMap spatial filtering.

5.2.4. Land/Water Separation

Due to the optical characteristics of water that are close to opaque in the near infrared (NIR) range, the water appears dark in the infrared IR band. The dark (low digital values) of the NIR band are in contrast to the dry land areas that are appear bright (high digital values). As a result, the histogram of the NIR band over a coastal area is bi-modal (a digital value distribution of land and a digital value distribution of the water) (Figure 12). A threshold value between the two distributions is used for separating land from water in the NIR band. There are different approaches to evaluate the threshold values (sampling, profile, or using a histogram). The land water separation is conducted using the Raster Calculator tool in ArcMap. It is important to note that this land/water interface is the instantaneous shoreline that represents the shoreline at the acquisition time of the Landsat imagery. The bathymetry will be vertically corrected to the chart datum regardless of the water level to which this instantaneous shoreline corresponds (section 2.5.7).



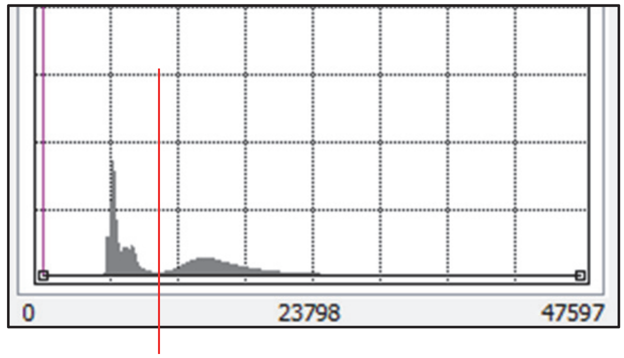


Figure 12. (Left) NIR image over Port-au-Prince, Haiti. (Right) The NIR image histogram showing the Land-Water threshold. For the NIR image, the land-water threshold was determined to be 10,000. Thus, any digital number greater than the threshold is considered land.

Appendix A.5 provides step by step procedure in ArcMap for land/water separation.

5.2.5. Radiometric Correction for Clouds and Sun Glint

A second radiometric correction is applied to remove cloud shadows and sun glint that appear on the water surface and may add errors to final product (Hedley et al., 2004):

$$\mathrm{L_{obs}}'(\lambda_i) = (\mathrm{L_{obs}}(\lambda_i)) - b_i \cdot \left((\mathrm{L_{obs}}(NIR)) - Min(\mathrm{L_{obs}}(NIR))\right) \qquad (2)$$

where the pixel value in band i, $L_{obs}(\lambda_i)$, is reduced by the product of regression slope, b_i, and the difference between the pixel NIR value, $L_{obs}(NIR)$, and the ambient NIR level, $(Min(L_{obs}(NIR))$. The result is a radiometrically corrected pixel that represents the pixel value of a given band without any radiometric contributions from clouds or sun glint.

Appendix A.5 provides step by step procedure in ArcMap for cloud and sun glint removal.

5.2.6. Generation of the Algorithm Result

The ratio transform approach utilizes two bands to reduce the number of parameters required to infer depth. This requires less empirical tuning and therefore a more robust algorithm to the linear transform approach (Stumpf et al., 2003). Assuming a uniform mixture in the water column, the ratio of two bands will maintain a near-constant attenuation value that is the difference of the diffuse attenuation coefficient at two different wavelengths. The concept for both algorithms using the ratio approach is that bottom radiance of one channel will decay faster with depth than the other band (Dierssen et al., 2003; Stumpf et al., 2003). As a result, the ratio between the two bands will increase as depth increases. This procedure utilizes Stumpf et al. (2003) log ratio approach, where the bathymetry was extracted from a natural log ratio between the blue and green bands:

$$z = m_1 \left(\frac{ln(n\mathrm{L_{obs}}(\lambda_i))}{ln(n\mathrm{L_{obs}}(\lambda_j))} \right) - m_0 \qquad (3)$$

where m_1 is the tunable constant to scale the ratio to depth, n is a fixed constant for all areas and m_o is the offset for a depth of 0 m (Z=0). The value of n is chosen to ensure that the logarithm will be positive under all circumstances and the ratio will produce a linear response.

Appendix A.6 provides step by step procedure in ArcMap for applying the log ratio algorithm.

5.2.7. Selection of Reference Soundings

In order to calculate the gain and offset values (Equation 3), the algorithm results were compared and correlated to the chart soundings. Typically, the two main considerations for selecting reference soundings are (Figure 13): 1) a source diagram that indicates the survey period and the survey technology and 2) a visual correlation between the optically-driven bathymetry and the chart's contours and soundings. Although the instantaneous water level at the time of satellite image acquisition is very unlikely to coincide with the chart datum (e.g., Mean Lower Low Water (MLLW) or Lowest Astronomical Tide (LAT)), there is no need to measure the tide height during the image acquisition, because this is automatically accounted for using control points that are selected from a nautical chart to determine the transformation parameters. Differences in water levels are usually well approximated as a vertical offset and do not impair the linear relationship between chart soundings and ratio algorithm output.

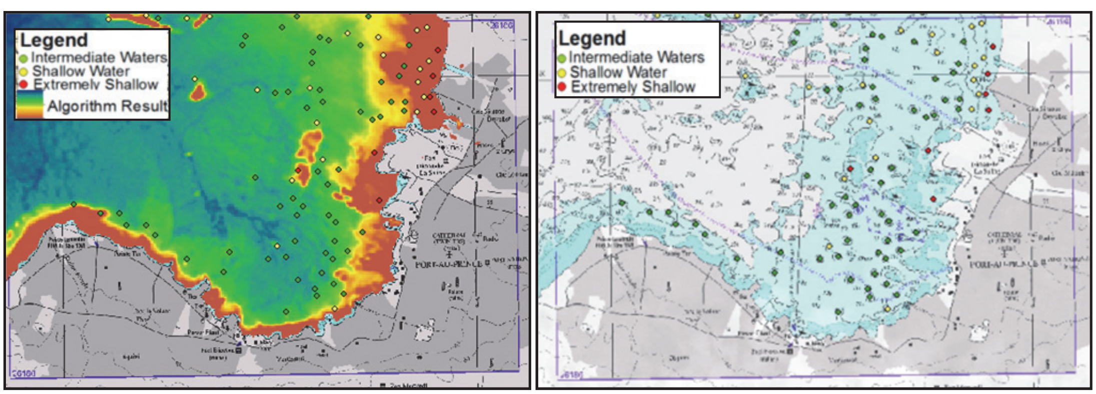


Figure 13. An example for sounding selection based on the algorithm results and the source diagram (Port-au-Prince, Haiti).

5.2.8. Evaluating the Extinction Depth, Gain, and Offset

The averaged values of the optically-driven bathymetry were plotted against the chart soundings and the satellite-derived bathymetry (Figure 14). This plot facilitates the identification of the extinction depth, which is the boundary between visible seafloor morphology (optically-shallow waters) and the suspended sediment area and/or the optically-deep area. In the optically shallow waters, a linear trend is noticed between the chart soundings and the satellite-derived bathymetry from which the gain, m_1, and offset, m_0, are extracted. Although it is possible to identify seafloor features beyond the extinction depth, it is hard to provide a reliable depth measurement on these features.

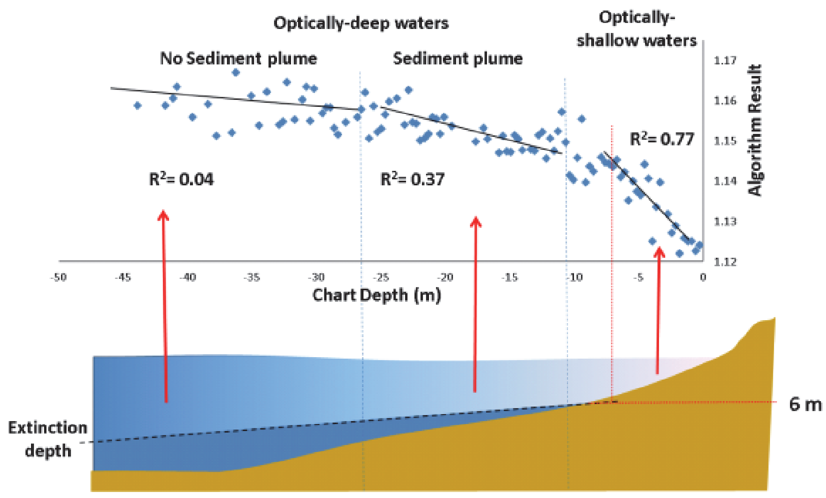


Figure 14. A schematic illustration of the statistical analysis at the calibration site using the Blue-Green Stumpf et al. (2003) algorithm with a low-pass filter. Top part of the image shows the scatter plot of the algorithm's results as a function of the chart sounding (MLLW). The bottom part of the image provides a possible explanation for the algorithm results and their relation to the depth of extinction.

Appendix A.7 provides step by step procedure in MS Excel for the calculation of the extinction depth, gain and offset.

5.2.9. Vertical Referencing of the Algorithm Result to the Chart Datum

After fitting a linear trend through the scatter plot for depths shallower than the extinction using regression analysis, the gain and offset values are calculated. Thus, the algorithm result is referenced to the chart datum. In cases where the unit of the chart are mixed (fathoms and feet), it is better to convert the sounding to one set of units (e.g., decimal fathoms).

Appendix A.7 also provides step by step procedure in ArcMap for applying gain and offset to the algorithm result.

5.2.10. Statistical Analysis

This last step is a quality assurance for the procedure that includes an internal evaluation and an external evaluation. The internal evaluation is namely the correlation coefficient calculation that indicates the linearity between the datasets, also known as R^2 (Pearson correlation coefficient). Also, changes in gain and the offset values are assessed by changing the depth range used for fitting a linear trend. The internal evaluation allows assessing of the relative accuracy of the results. The external calculation is a statistical comparison with a visual illustration (e.g., histogram and scatter plot) between the final bathymetry product and the soundings. The external evaluation allows assessing the absolute accuracy of the results.

Appendix A.8 also provides step by step procedure for conducting a statistical analysis.

6. RESULTS

6.1. Port-au-Prince, Haiti

Two satellite images were acquired over Port-au-Prince: 1) Landsat 8 image from April 16, 2013 and 2) WV-2 image from June 14, 2013. The satellite algorithm was referenced to Mean Lower Low Water (MLLW) using the ENC sounding layer (S-57 SOUNDG feature) derived from NGA Charts 26186 ("Approach to Port-au-Prince," Scale: 1:50:000) and 26184 ("Port-au-Prince," Scale: 1:10,000). The specific soundings that were used to derive bathymetry were sampled from the offshore area south of Port-au-Prince. This area was surveyed in 2010 by the U.S. Navy at a scale of 1:1,000 (Archive No. SF401024). The final bathymetry product was clipped to the coverage area of NGA Chart 26184 (Figure 15).

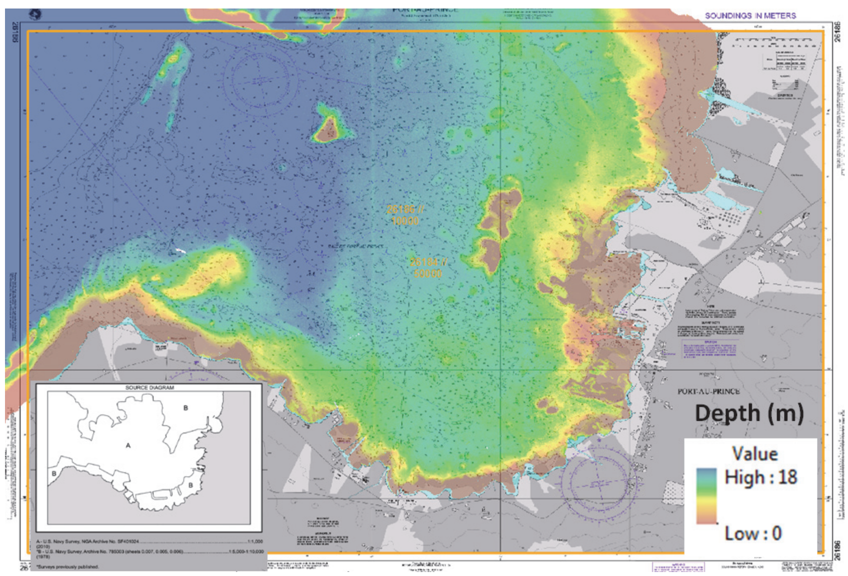


Figure 15. Satellite-derived bathymetry using WV-2 over Port-au-Prince, Haiti overlaid on NGS Chart 26184.

The algorithm results from both satellite imagery looked similar to the chart bathymetry (R^2= 0.82). The calculated extinction depth is around 14.5 m below MLLW for Landsat 8 and around 18 m for WV-2. The environmental issues identified in the image are water turbidly that occurred at the mouth of several rivers (e.g., Riviere Froide and Grande Riviere du Cul de Sac) (Figure 16). Such turbidity may be misinterpreted as shoal areas in the satellite-derived bathymetry procedure. In addition to the environmental issues, there seems to be a striping effect based on the WV2 scanner. This artifact does not affect the final results.

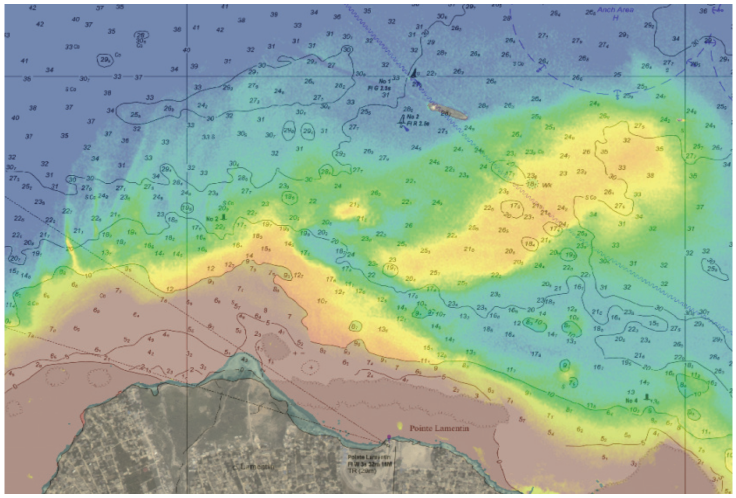


Figure 16. Sediment plume output from Riviere Froide observed as shoal in the satellite-derived bathymetry procedure.

6.2. Baie de l'acul, Haiti

Two satellite images were acquired over Baie de l'Acul: 1) Landsat 8 image from August 1, 2013 and 2) WV-2 image from Oct 16, 2012. No cloud cover was observed in both satellite images. The satellite-derived bathymetry algorithm was referenced using the ENC sounding layer (SOUNDG feature) derived from NGA Charts 26142 ("Approaches to Cap-Haitien and Bahia de Monte Cristi," Scale: 1:75:000) and 26148 ("Baie de l'Acul and Approaches," Scale: 1:20,000). Bathymetry was derived from the offshore areas Labadee Nord (east of Cap-Haiten) in the area overlapping the two satellite images and was referenced to the chart datum (MLLW). The final bathymetry product was clipped to the coverage area of NGA Chart 26148 (Figure 17).

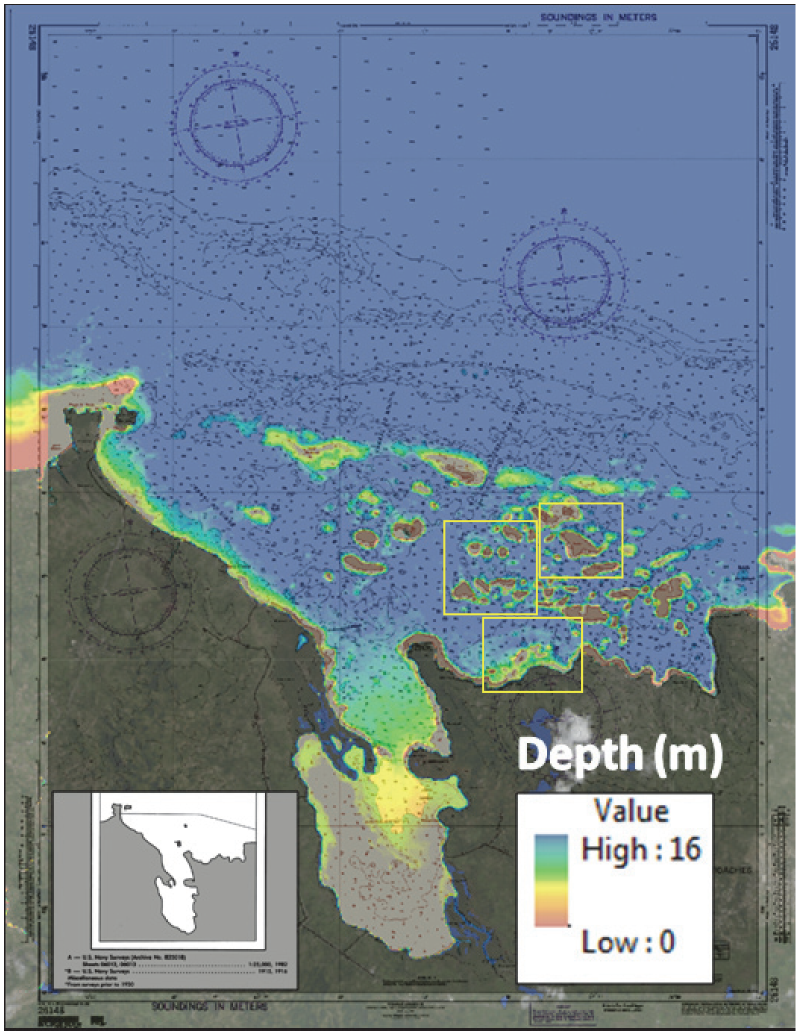


Figure 17. Satellite-derived bathymetry using Landsat 8 over Baie de l'Acul, Haiti overlaid on NGS Chart 26148.

The extinction depth for both Landsat 8 and WV2 satellite imagery was calculated at about 16 m below MLLW. Although the survey period between the satellite imagery (2013) and the surveys used within the chart (1916) are almost 100 years apart, it seems that the algorithm results from both satellites are similar to the charted bathymetry ($R^2 > 0.95$). A closer look at three sites (Figure 18) shows that the area of the charted shallow coral reefs has grown and additional shallow reef may be present (Figure 18, left image). The water clarity outside of the bay's straits seems to be clear.

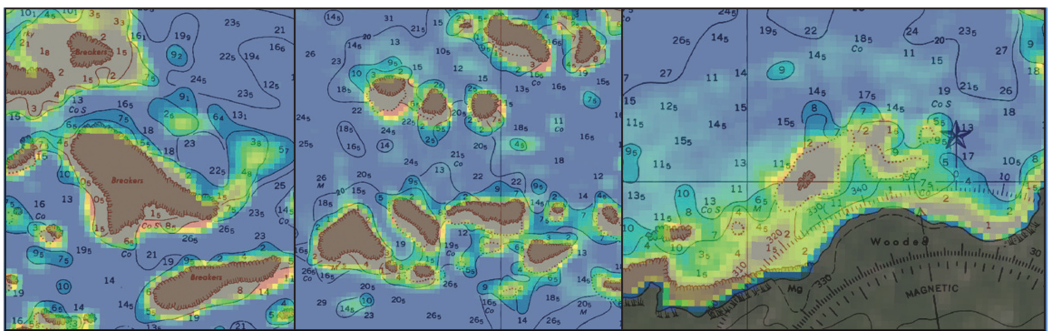


Figure 18. Close inspection sites that were used evaluate the chart's bathymetry.

7. DISCUSSIONS

The use of commercial satellite imagery to evaluate the bathymetry of charts over Haiti seemed to be successful. Both datasets of satellite imagery (Landsat 8 and WV-2) provided similar results. The main difference was the resolution and coverage between the two sets of imagery. Landsat 8 imagery provided a larger coverage (swath width of 185 km), whereas WV-2 has a swath width of 18 km. It is recommended to start the procedure with Landsat 8 imagery because a single image can cover an area displayed by a 1:75,000 chart (Figure 19) and 4 to 6 Landsat 8 images can cover Haiti in its entirety.

Figure 19. Landsat 8 versus WV-2 coverage over Port-au-Prince, Haiti. A WV-2 image (IR band) overlaid on NGS Chart 26184 (1:50,000). The NGA chart is overlaid on a Landsat 8 image (RGB image).

WV-2 imagery is useful when inspecting anomalies in the bathymetry (e.g., shoals). Although Landsat-8 can indicate the presence of a shoal, its ground resolution is coarse (28.5 m). The high resolution of WV-2 (~ 2 m) allows a closer inspection of the anomaly at a resolution that is greater than the chart's scale. Figures 20 and 21 provide a visual comparison between Landsat 8 and WV-2 over shoal water areas.

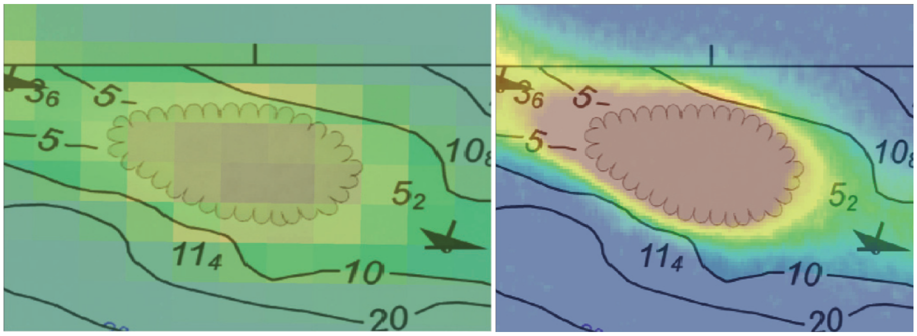


Figure 20. Bathymetry derived from Landsat 8 imagery (left) and WV2 imagery (right) over a shoal in Port-au-Prince, Haiti.

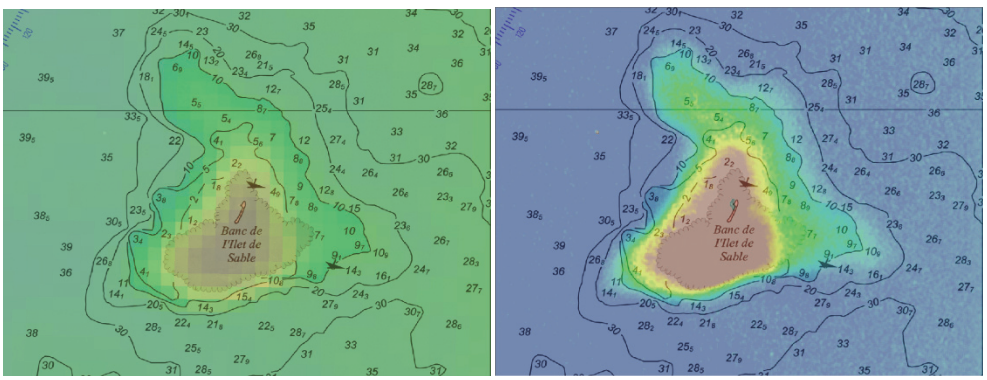


Figure 21. Bathymetry derived from Landsat 8 imagery (left) and WV2 imagery (right) over a shoal in Port-au-Prince, Haiti.

Based on the results in Port-au-Prince, Haiti, it is important to identify clouds and sediment plumes in the imagery. These areas should be masked and should not be used in the comparison between the satellite-derived bathymetry and the chart. Otherwise, errors in bathymetry might be introduced.

The procedure was able to evaluate historical survey data on the charts and confirm that it is still valid for safe navigation. Although satellite-derived bathymetry is a reconnaissance tool that cannot confirm or disprove a sounding with complete confidence, it can focus resources to refined areas on the chart.

8. RECOMMENDATIONS

The current recommendation is that no further action is required.

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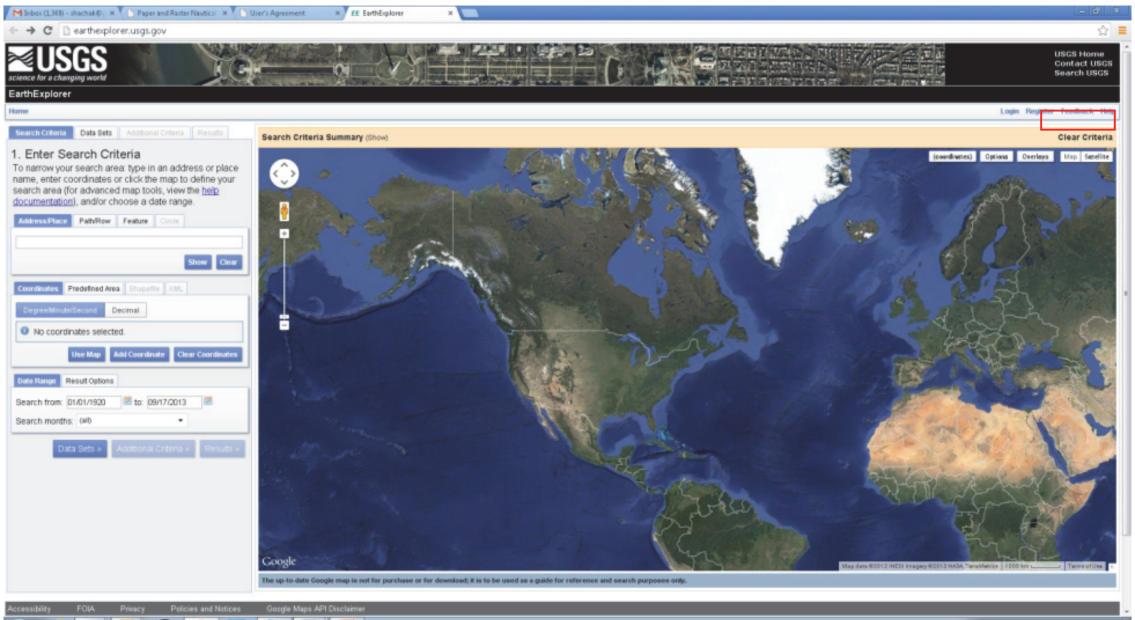
APPENDIX A. SATELLITE DERIVED BATHYMETRY PROCEDURE

A.1 Downloading Satellite Imagery

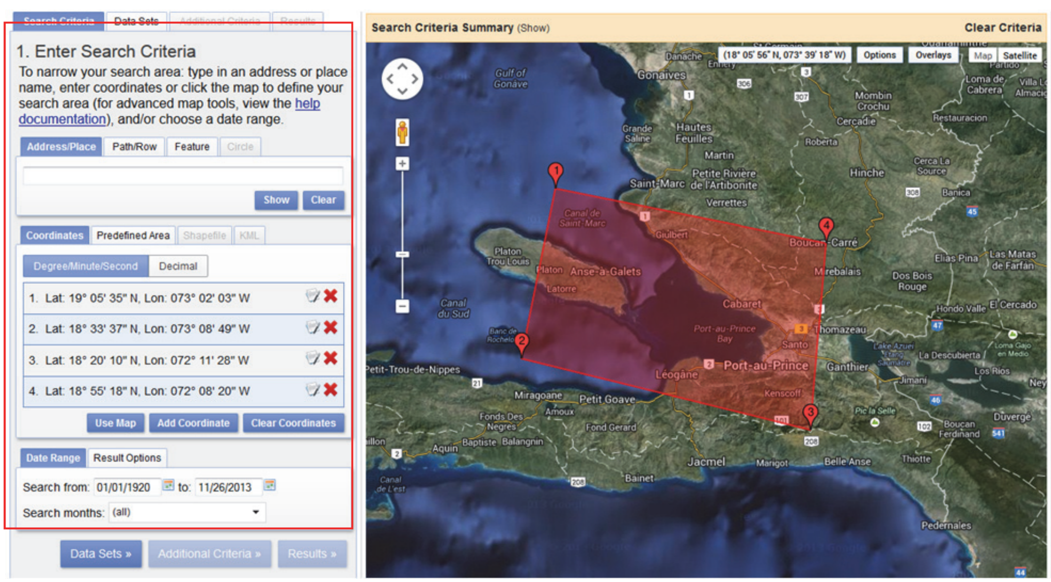
A.1.1 Downloading A Landsat 8 Imagery

Open a Web Browser and go to http://earthexplorer.usgs.gov/. Login into your account (the Login button is upper right corner of the window).

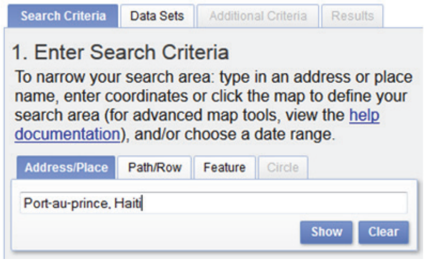


Note: The service is free, but the website requires user to login. Users that are accessing this site for first time need to register (the **Register** button is upper left corner of the window).

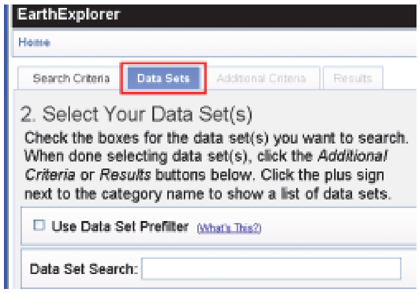
Zoom into the desired region. Create a square around the desired region by clicking on the corners of the area. The polygon vertex coordinates will appear in the Search Criteria tab.



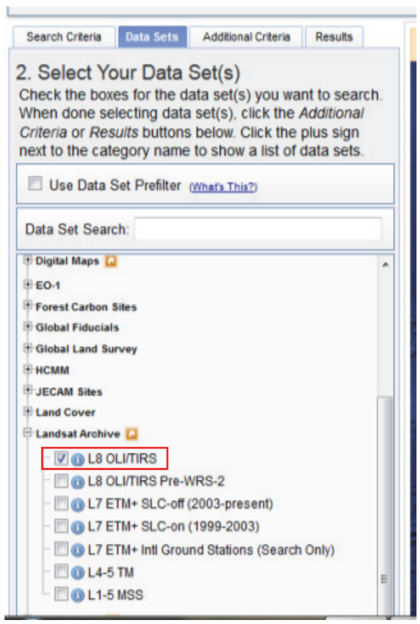
Alternatively, type in a location you are interested and the country in the **Address/Place** located under the **Search Criteria** tab and click on **Show**. Select the site of interest from the a list of possible sites with similar names and the location will be shown on the map



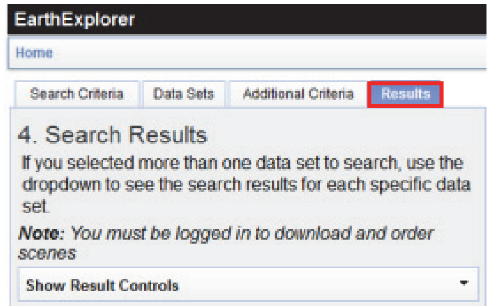
On the top left side of the screen, click on the ***Data Sets*** tab.



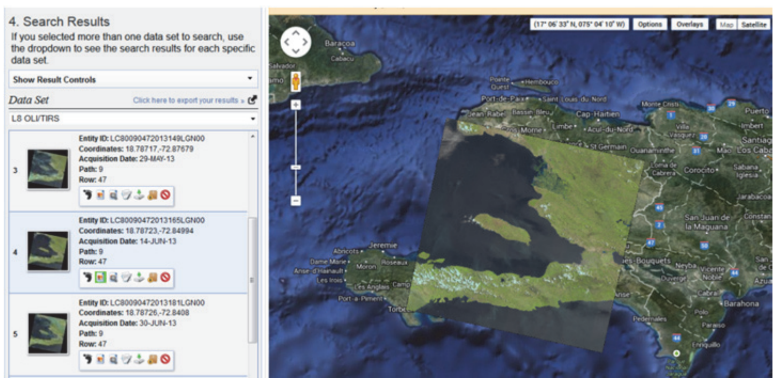
Expand the **Landsat Archive** and select **L8 OLI/TIRS** for Landsat8 imagery.



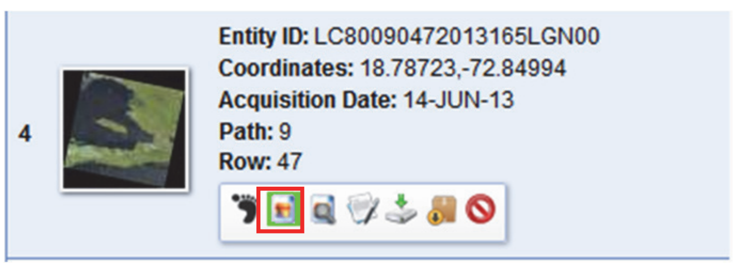
Select the ***Results*** tab.



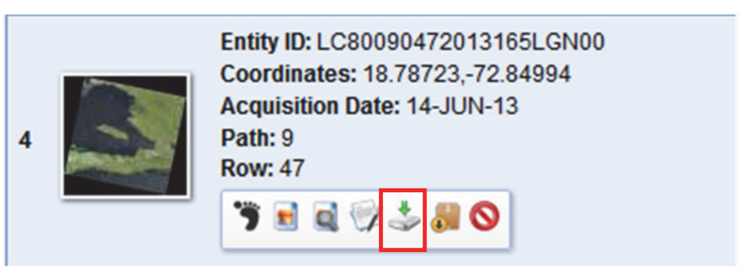
Scroll down and look at the quick view results. Select the download icon of the desired data set.



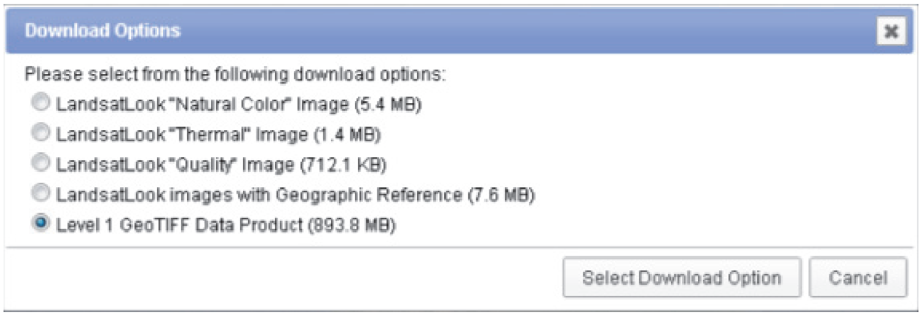
Before selecting the image, it is possible to preview the image by clicking on ***Show Browse Overlay***.



Select ***Download*** to display the area you are interested to process.

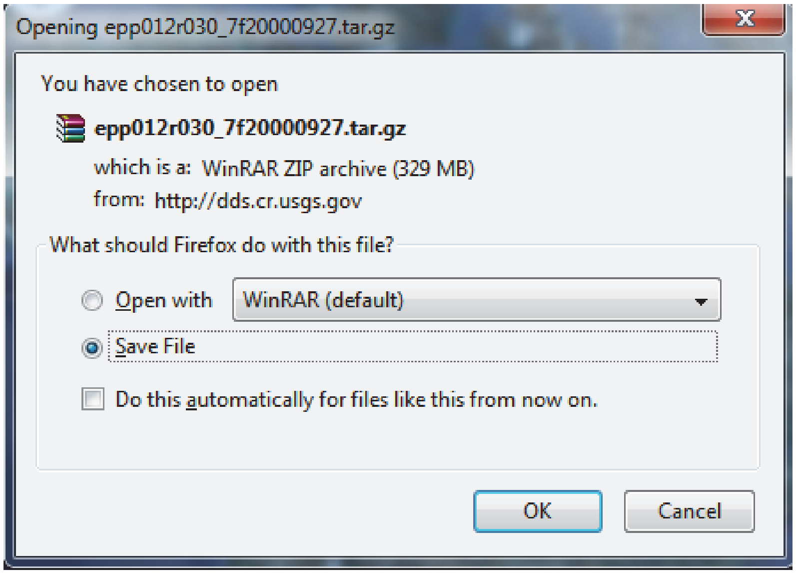


Select ***Level 1 GeoTiff Data Product*** and press ***Select Download Option***.



Press ***Download*** in the **Download Scheme** window.

Save the file in your data directory and press ***OK***. Make sure to unzip the chart to your data directory.

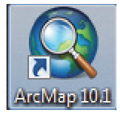


A.1.2 Downloading A WV-2 Imagery

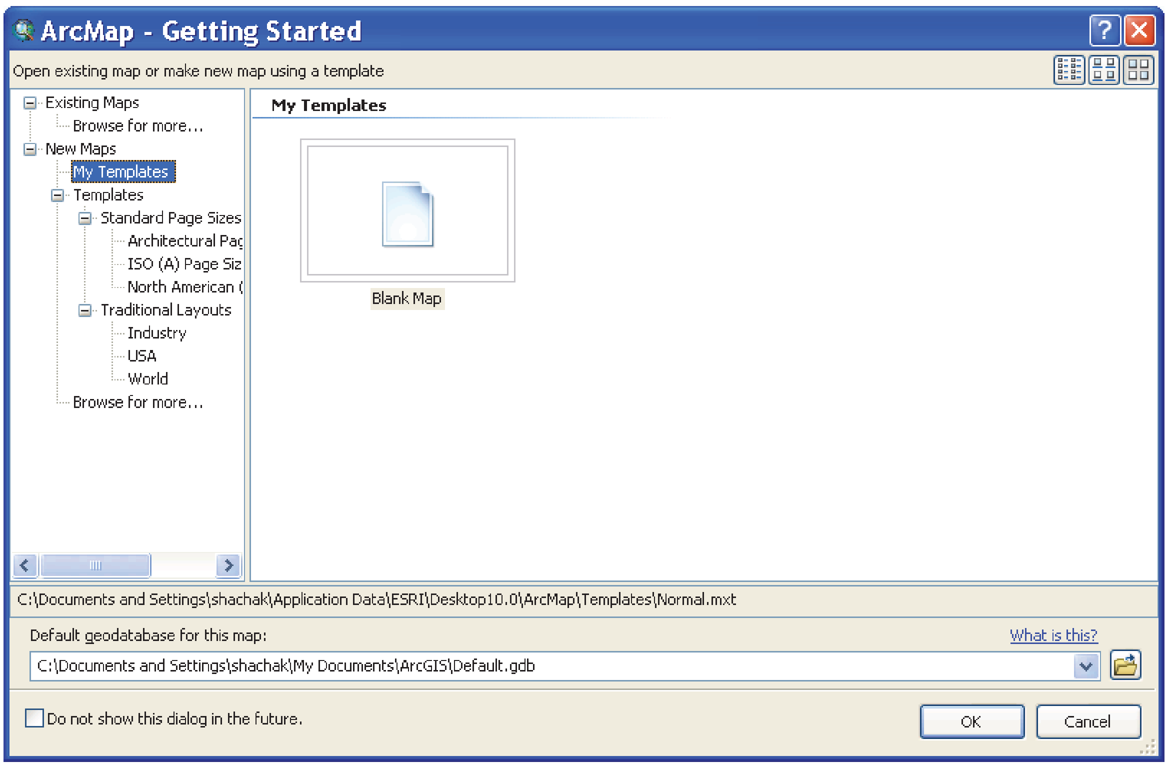
For Internal U.S. Federal Use Only - Documentation Is Provided As A Separate File

A.2 Setting up the GIS Environment

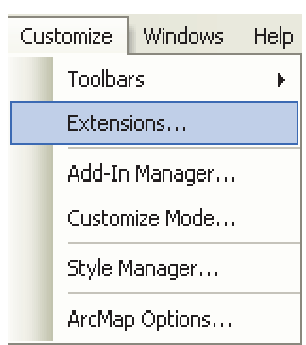
Open ArcMap.



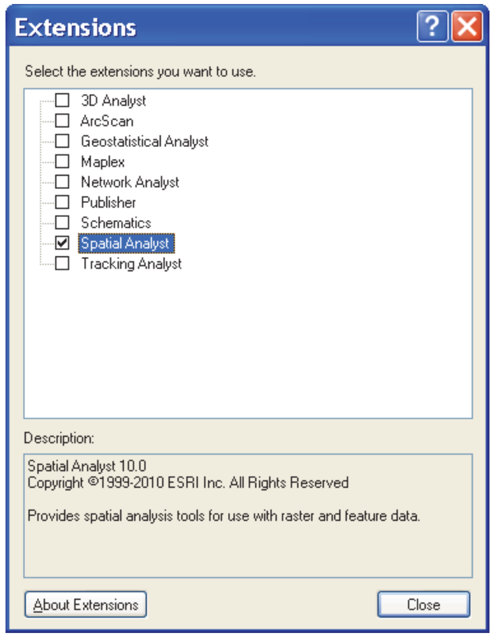
Depending on your set up, you may get the following window. Press ***OK***.



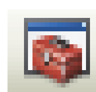
Select ***Extensions…***Under the ***Customize*** Tab.



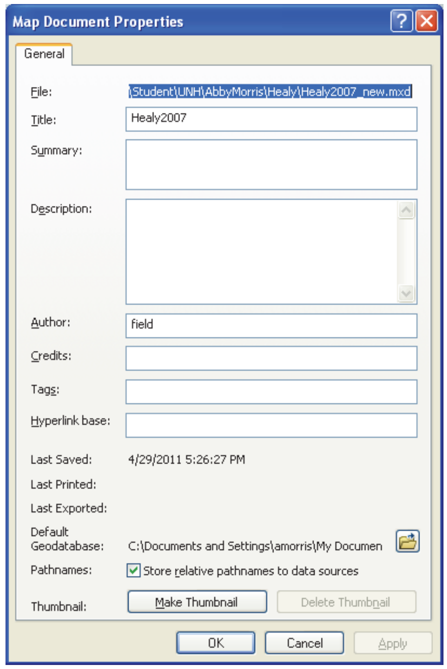
In the ***Extensions*** window, mark **Spatial Analyst**. Press ***Close.***



Activate the **Toolbox** by clicking on the icon in the upper toolbar.



Click on file and open **Map Document Properties**. Check the box for **Store relative pathnames** to data sources and click ***OK***.



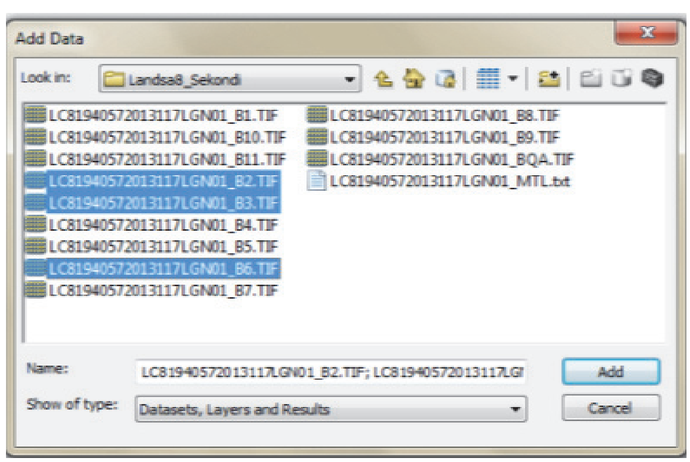
A.3 Loading the Datasets in ArcMap

A.3.1 Satellite Imagery

<u>**Note**</u>: Landsat imagery is typically download as separate imagery files and not as a RGB image.

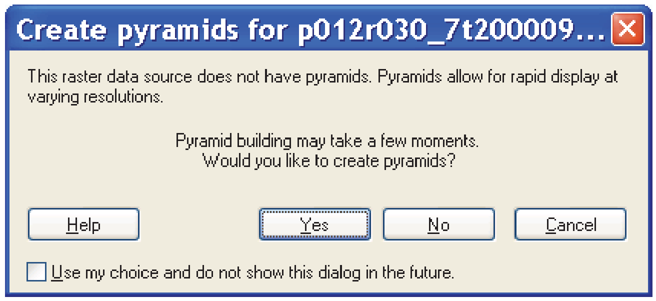
Load the satellite data to ArcMap by selecting ***Add Data***…

Navigate to your directory and select the satellite image in the **Add Data** window and select ***Add*** button. The Blue, Green and Infrared band in Landsat 8 are numbers as: *_B2.tif, *_B3.tif, and *_B6.tif, respectively.

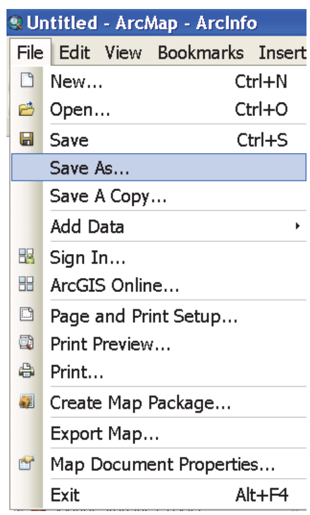


<u>Note:</u> If your imagery is not on your computer, you will need to use the **Connect to Directory**in otder to link your project to your computer.

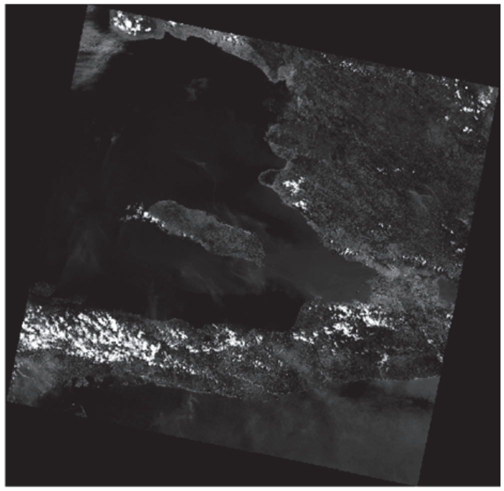
In case you are asked to create pyramids, press ***Yes***.



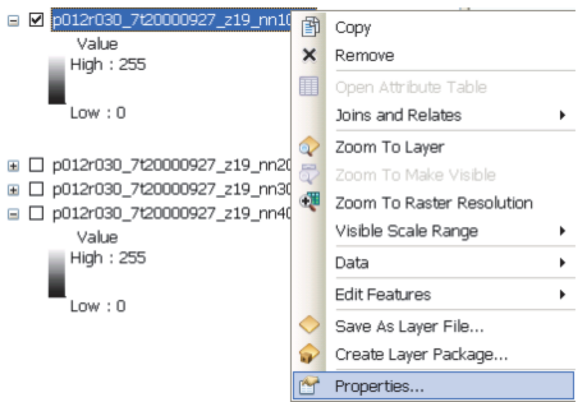
Save your project by selecting **File/ Save As…** .



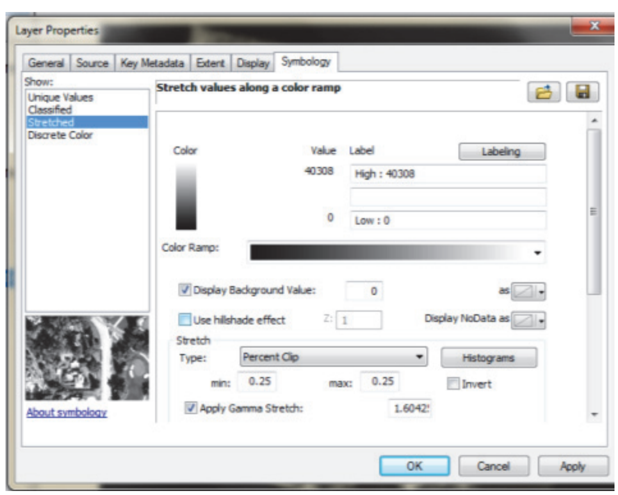
The satellite imagery will be loaded with black background.



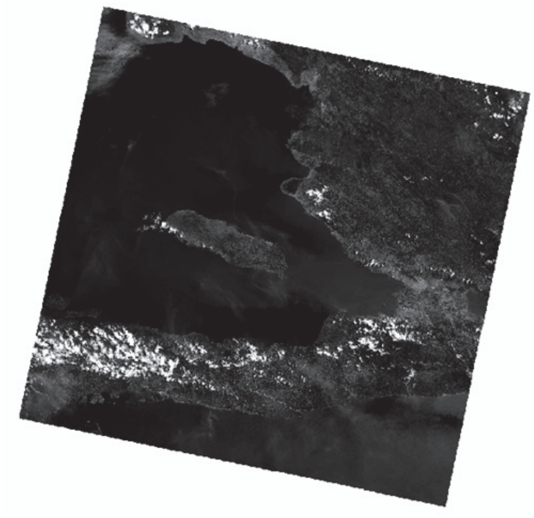
Right click on the image layer and select the ***Properties…*** button.



In the **Symbology** tab, mark the ***Display Background Value*** (in this case black is when the value is 0).



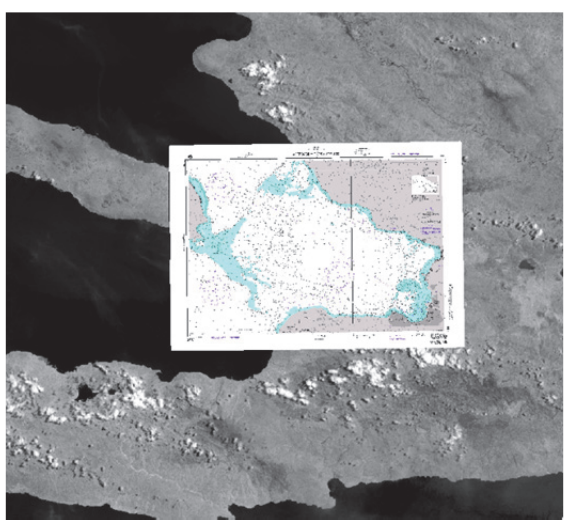
Press the ***Apply*** button and then the ***OK*** button in the Layer Properties window. Now the layer is without the black background. Repeat steps to remove background for the other layers.



A.3.2 Nautical Chart

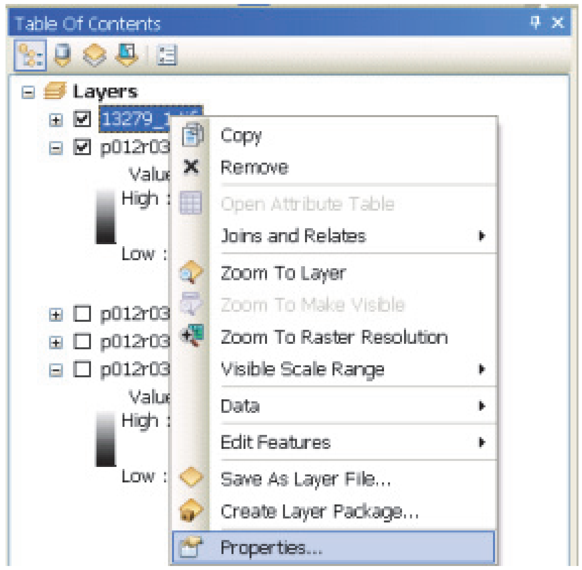
Load the nautical chart to ArcMap by right-clicking on the desired directory and select ***Add Data***…

The chart is displayed over the satellite imagery.

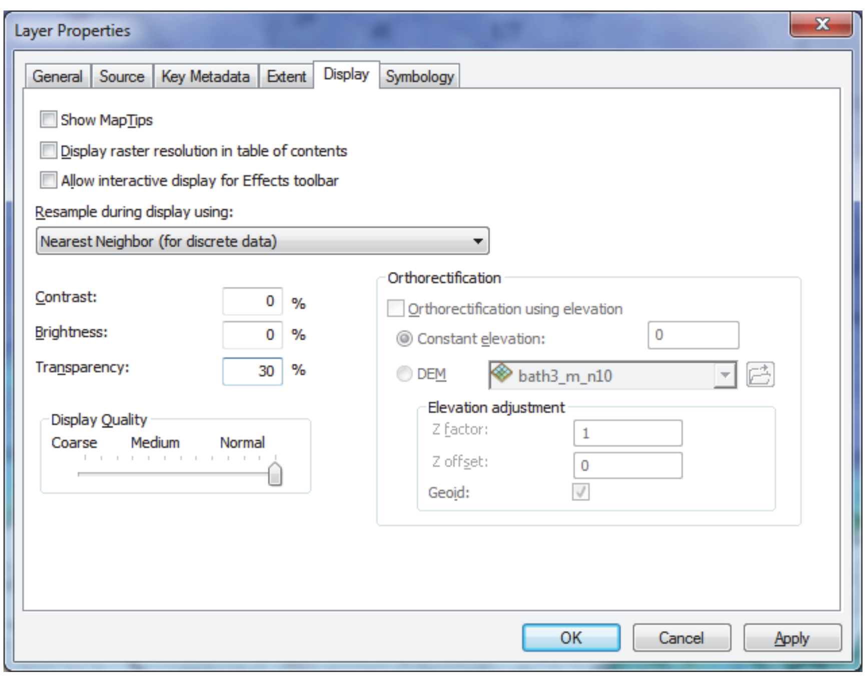


.

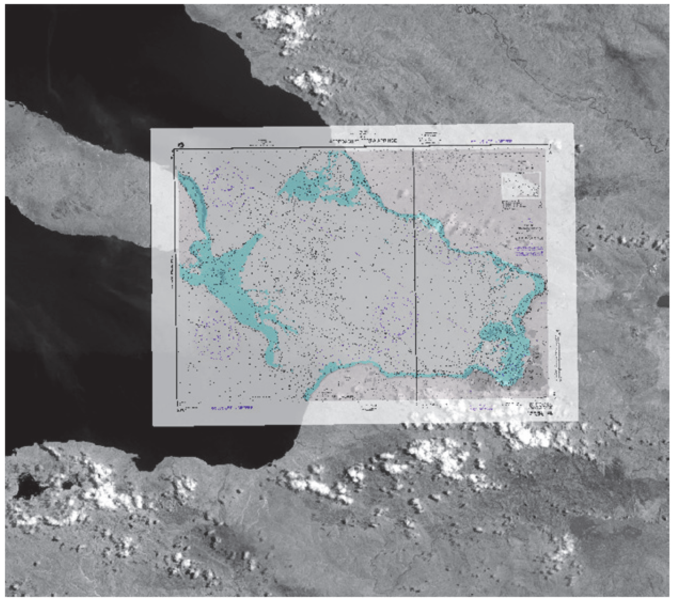
Right click the chart layer and select ***properties***.



Select the ***Display*** tab and set the ***Transparency*** to 30% and press ***OK***.



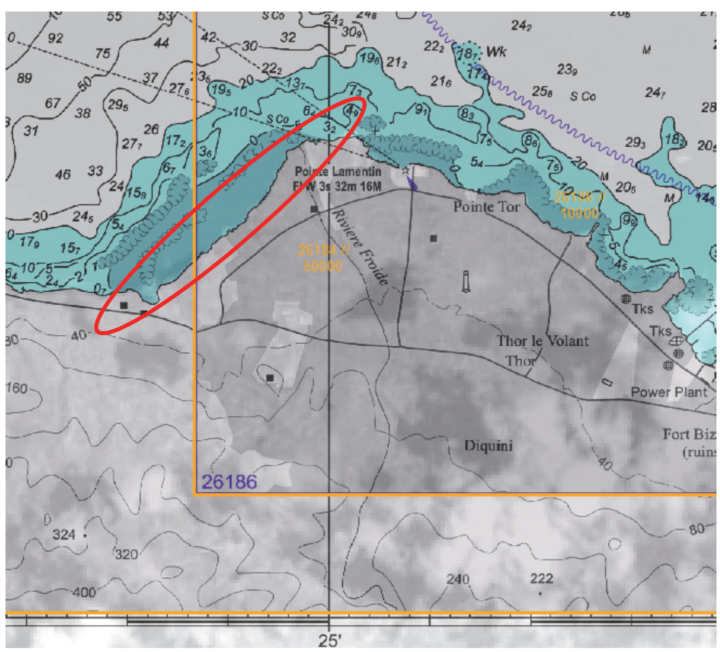
The chart will appear and also the imagery layer below. Make sure the satellite and the chart are registered correctly.



A.4 Horizontally Referencing

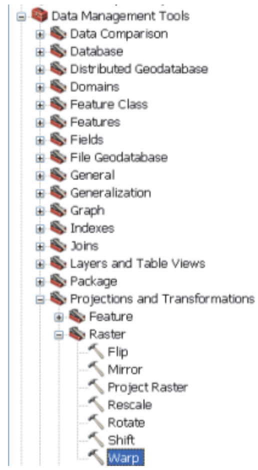
It is important to check if the chart and the satellite imagery overlap well. If not, select the **Zoom In** (magnify) icon.

Zoom in to location where the shoreline (or road junction) in the satellite imagery is also identified on the chart. In this case, the charted shoreline and satellite imagery match.

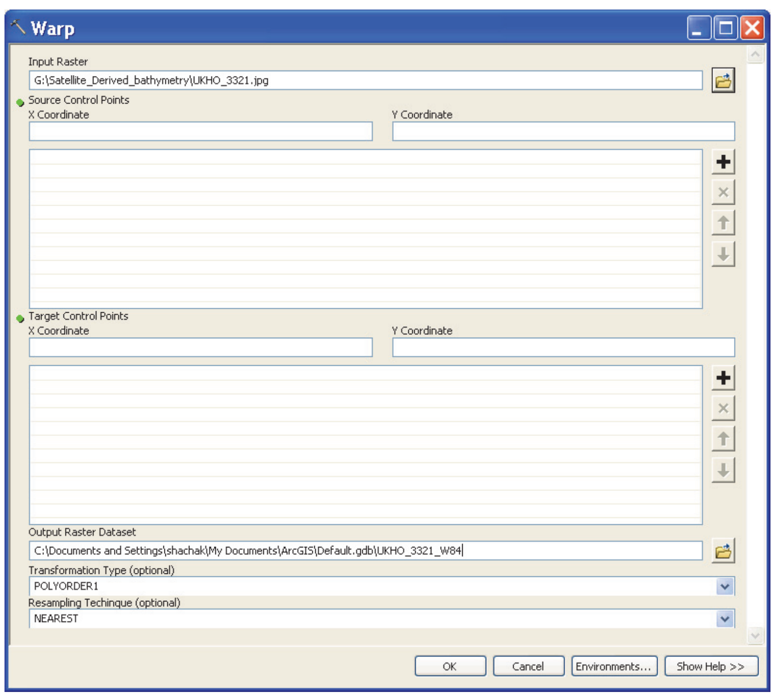


If the chart and imagery do not align, proceed below. __Note:__ For the purposes of this procedure, an example of an unreferenced UKHO chart has been used.

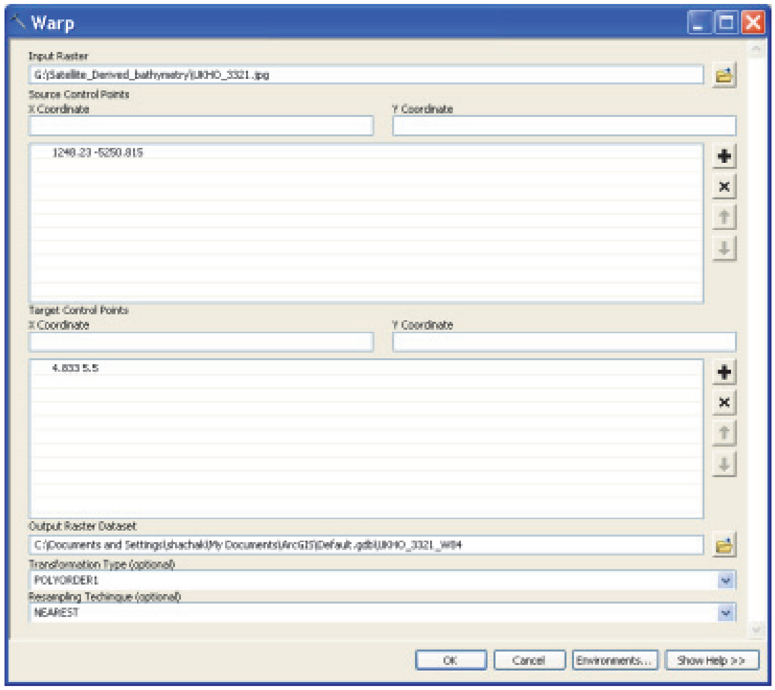
Select **Data Management Tools/Projections and Transformations/Raster/Warp** in the **Toolbox** window.



Load the input raster (i.e., the satellite imagery) as **Input Raster** in the **Warp** window. Note the horizontal reference system used for the satellite image in the output raster dataset (in this example, WGS-84).

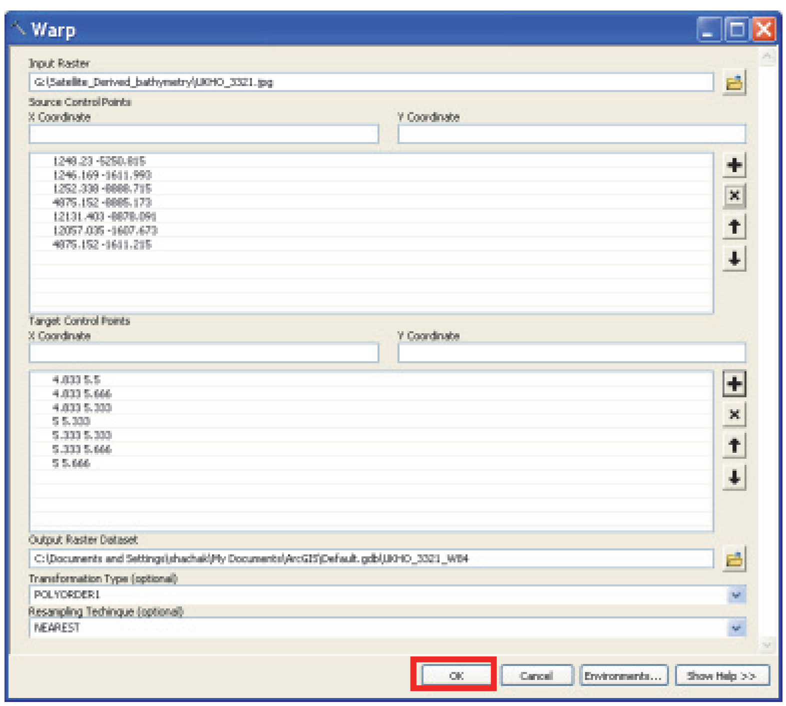


From the main view in ArcMap, start logging in the locations of the satellite image as Source **Control Points** and the chart position as **Target Control Points** into the **Warp** window. Collect more points around the satellite image.

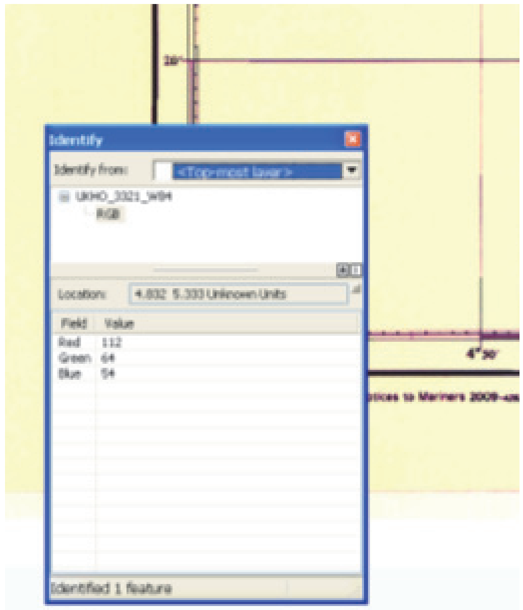


<u>Note:</u> Make sure to collect at least four points around the chart for a good referencing. Also make sure that the order of the target and source control points match.

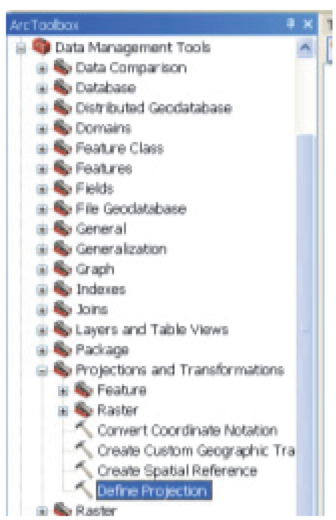
After you have sampled the control points, make sure that the **Transformation Type: POLYORDER1** and press **OK** in the **Warp** window.



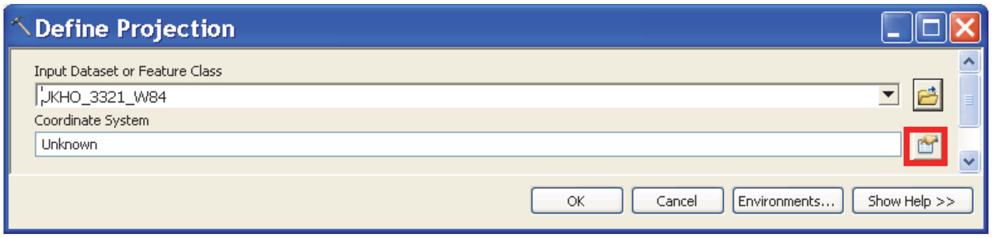
The warped image is now referenced to the horizontal reference system of the chart



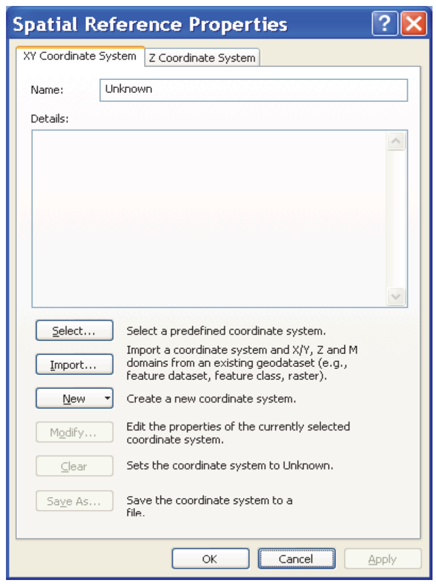
After the image has been warped, a reference system is assigned to the new file. Select **Data Management Tools/Projections and Transformations/Define Projection** in the **Toolbox** window.



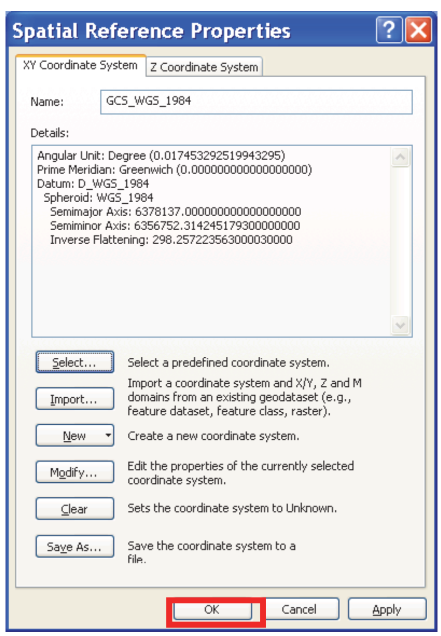
Load the warped image into the **Define Projection** window and press the **Select Reference Properties**.



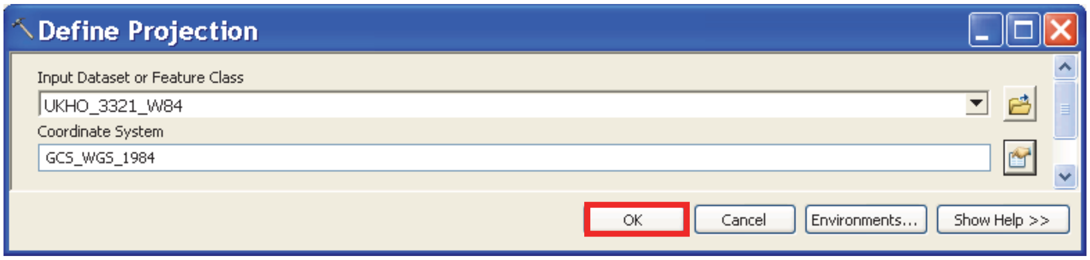
Press the **Select…** button in the **Select Reference Properties** window. In this example the reference system was **Geographic Coordinate System/World/WGS84.prj**.



After selecting a reference system, press **OK**.



Finally, press **OK** in the **Define Projection** window.



Load the new warped satellite image into the project.

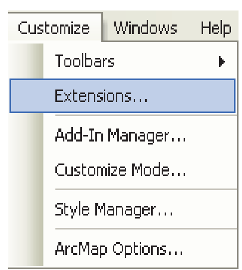
A.5 Land/Water Separation

A.5.1 Calculating the Water Threshold Value

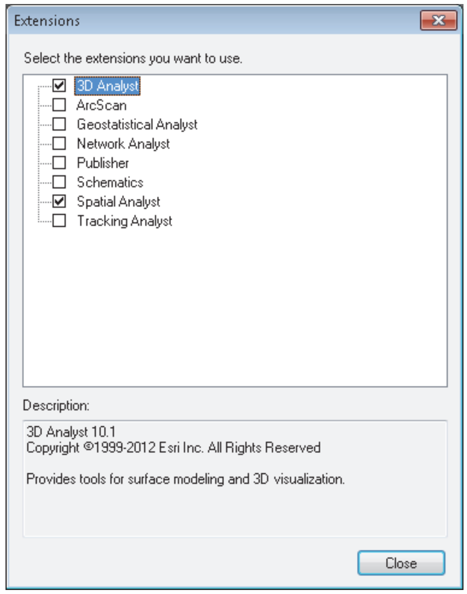
Note: There are several ways to calculate a threshold value for land/water separation. Three common options are: 1) **Profile,** 2) **Identify,** and 3) **Histogram**. A recommended approach is using the profile option, but this requires **3D Analyst** (not all users have this option under their current ArcMap license).

Option 1: Profile (using **3D Analyst**)

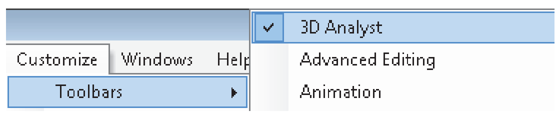
Select ***Extensions…***Under the ***Customize*** Tab.



In the ***Extensions*** window, mark **3D Analyst**. Press ***Close.***



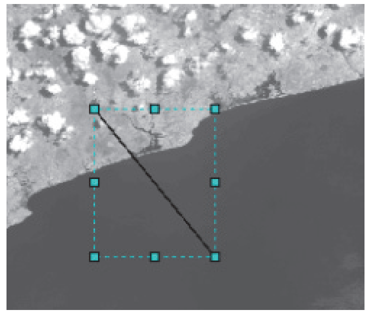
Activate the ***3D Analyst*** tool bar under the ***Customize/Toolbars***.



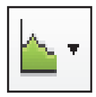
Select the infrared band (*_B6.tif in Landsat 8).

Press the ***Interpolate Line*** icon in the ***3D Analyst*** toolbar.

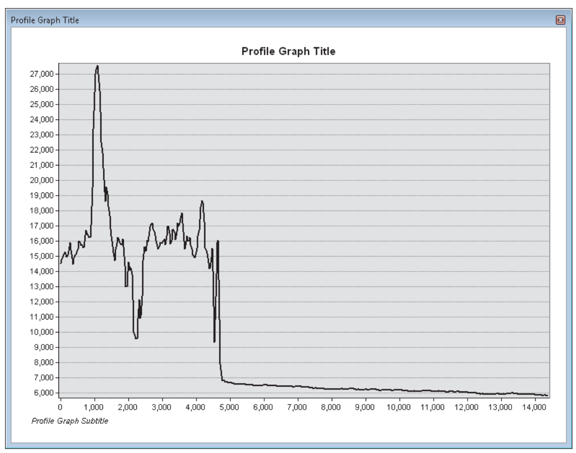
Make sure that the infrared band is visible in the project. Using the left button, draw a line that crosses from land (bright areas) into the water (dark areas). Finalize the line by double-clicking the left button.



After drawing the line the ***Profile Graph*** icon in the ***3D Analyst*** toolbar will be active. Press the ***Profile Graph*** icon.

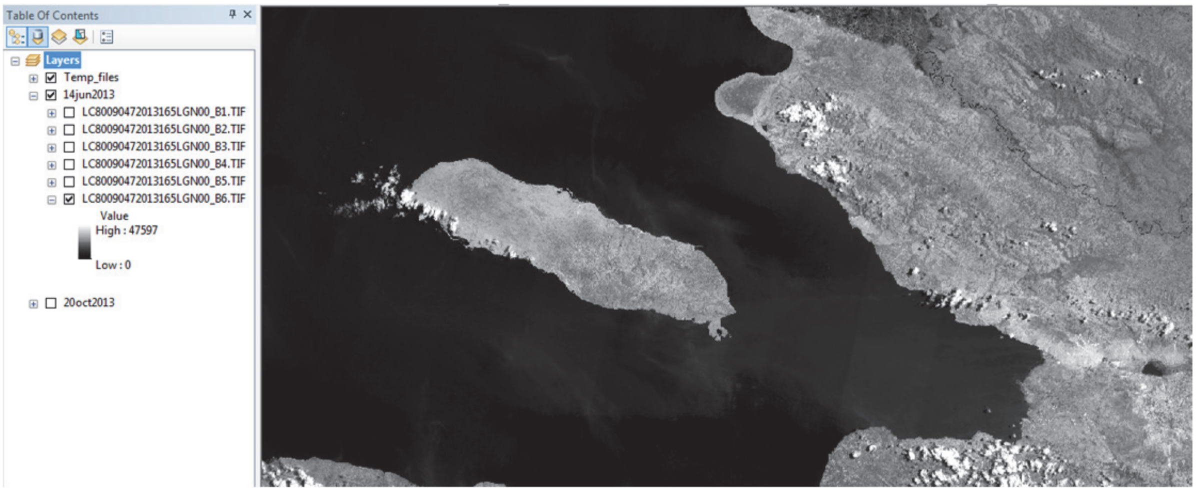


The result will be a plot that can be used to extract the land/water threshold. The smooth section with low values represents water, whereas the fluctuation high value areas represent land. In this case the threshold value is around 7000 (Landsat 8 image).



<u>**Option 2:** Identify</u>

Activate only the infrared band (*_B6.tif in Landsat 8).

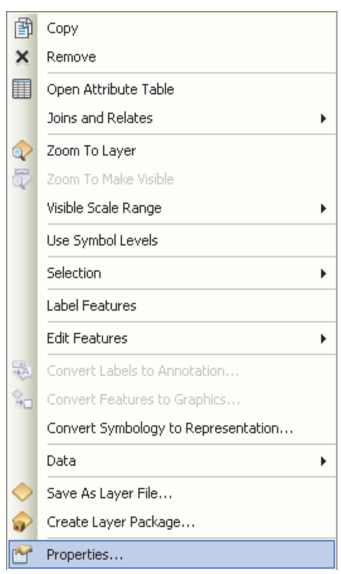


Select the ***Identify*** icon

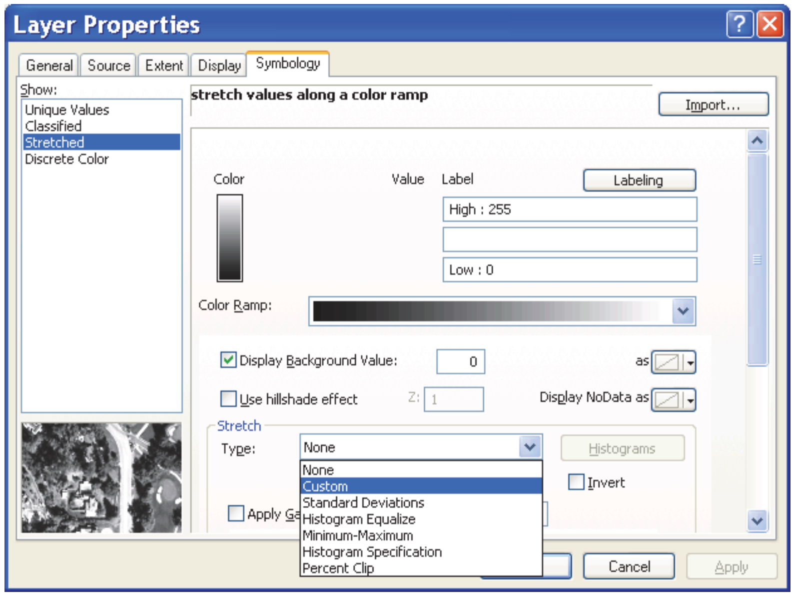
Click on several location over the water and write down the values. Then, click on several location over the land and write down the values. The threshold value should be between the water values and the land values.

<u>Option 3:</u> <u>Histogram</u>

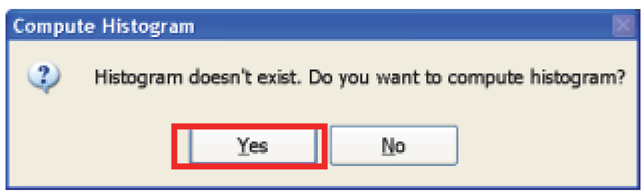
Right click on the infrared layer (in the **Table of Contents**) and select the ***Properties…*** button.



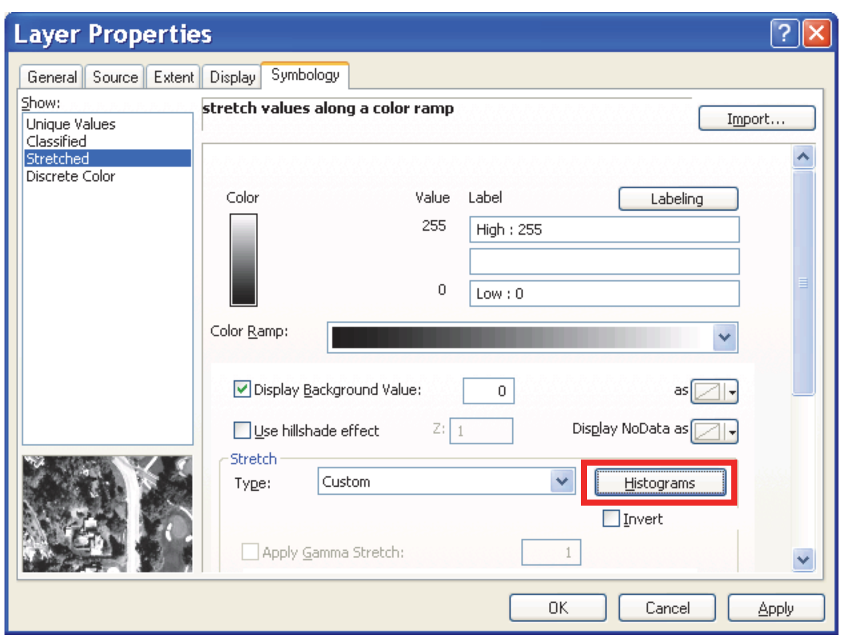
Activate the ***Symbology*** tab. Under ***Stretch***, select **Type: Custom**.



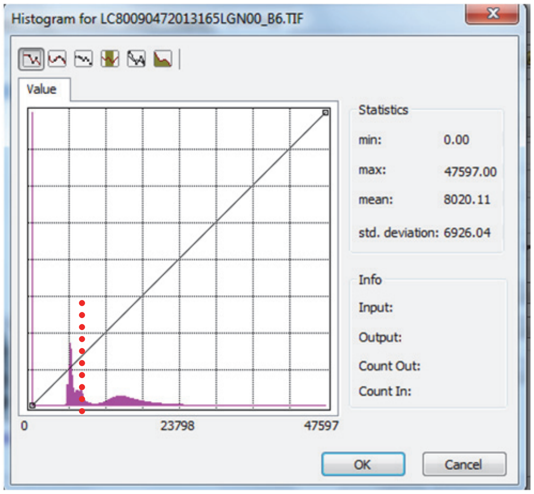
The following message will appear. Press ***Yes***.



Press the ***Histograms*** Button.



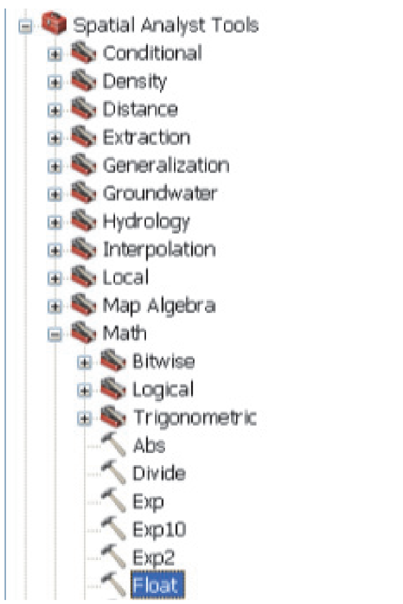
The Infrared Histogram will have two distinct peaks, one represents the land values (i.e., large values) and the other peak represents the water (i.e., values closer to 0).



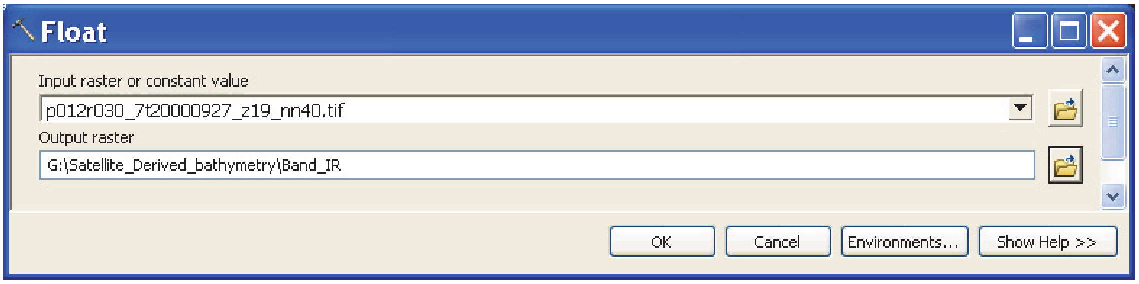
Move the mouse around the graph to determine the threshold by reading the input value (For this Landsat 8 layer it is about 10000). This is the threshold value that will be used to generate the water subset mask.

A.5.2 Generating a Water Subset

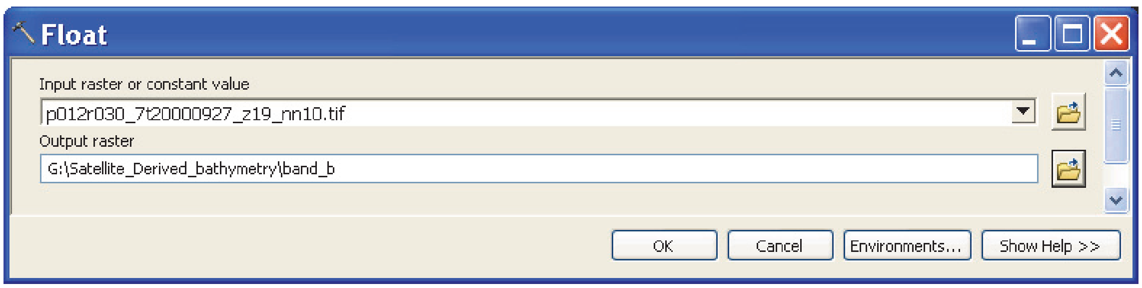
Convert the infrared band into float format, by selecting **Spatial Analyst Tools / Math / Float** from the toolbox.

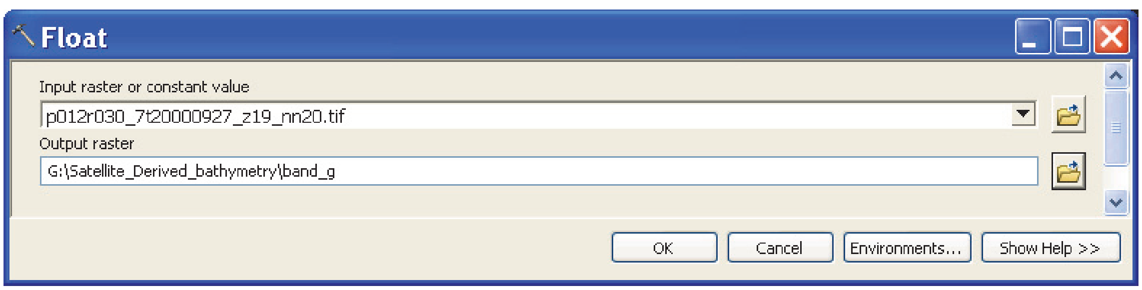


In the **Float** window, select the infrared band (*_B6.tif in Landsat 8) and type in an output raster. Press **OK**.

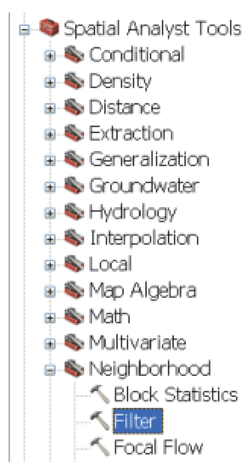


Repeat this step also for the blue (*_B2.tif in Landsat 8) and the green (*_B3.tif in Landsat 8) bands.

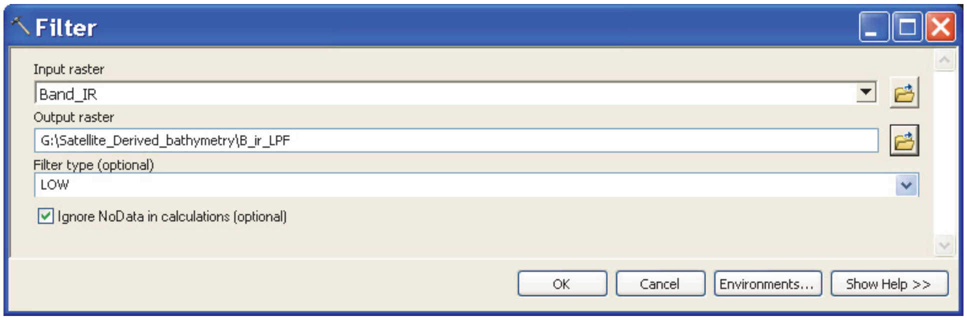




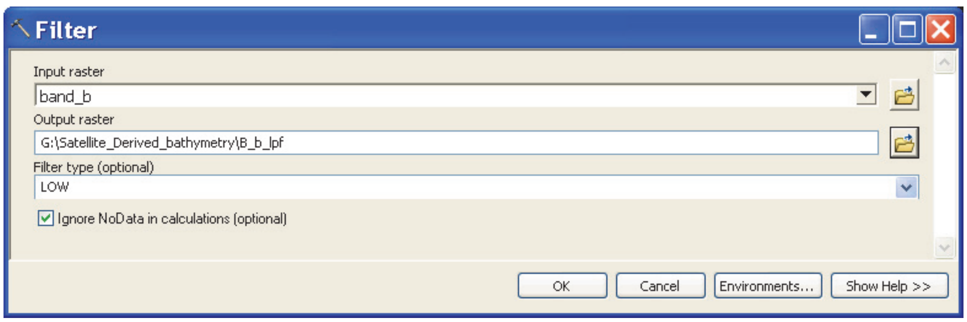
Next, apply a low pass filter by selecting **Spatial Analyst Tools / Neighborhood / Filter**

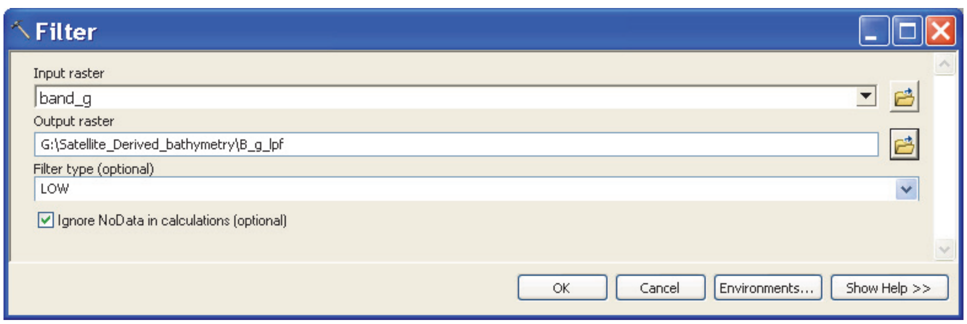


In the **Filter** window select the infrared band in float format and output raster. Also make sure the **Filter type (optional)** is **LOW**. Press **OK**.

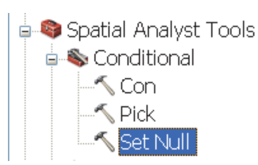


Repeat this step also for the blue and green float files.

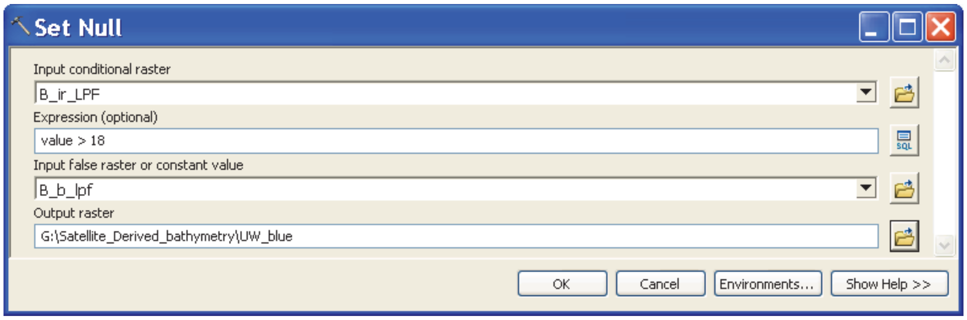




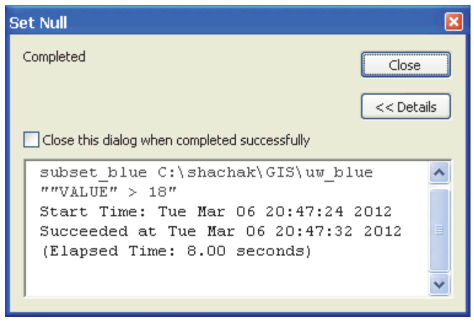
Remove the land from the blue and green imagery, by selecting **Spatial analyst Tools / Conditional / Set Null** in the **Toolbox** window.



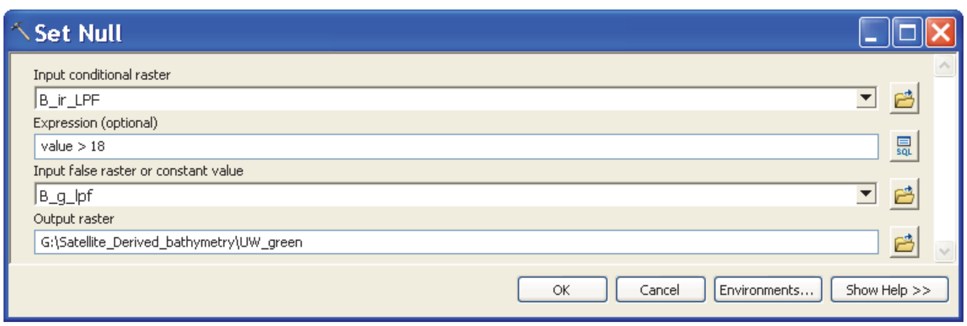
Fill the **Set Null** window as follows for the blue band and press ***OK***. Make sure that the threshold value in the expression is the value calculated in the histogram.



After the **Set Null** process has finished, press ***Close***.



Repeat this step also for the green band



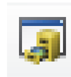
The new green and blue layer should contain areas only above the water.

Note: Make sure that the **Display background value** is set to 0 in the layer **Properties.**

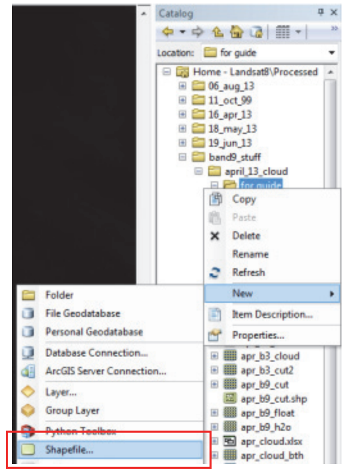
A.5.3 Glint/Cloud Correction

Note: The step is intended to correct radiometric contribution from low altitude clouds and glint from the Blue and Green band.

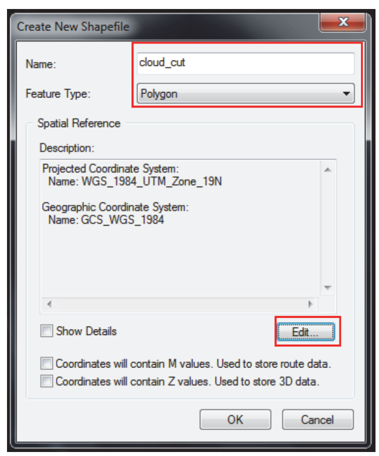
Open the **ArcCatalog**, by clicking on the following button.



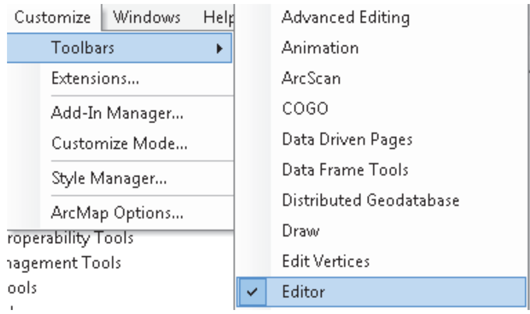
Right click on the folder where the layers are being saved and select ***New*** and then ***Shapefile***.



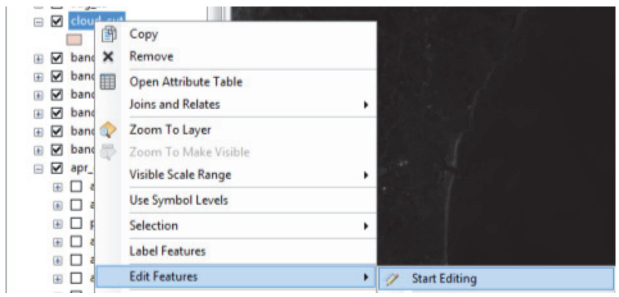
Select ***Polygon*** as the feature type, and name the file **cloud_cut**. Select ***Edit*** to change the coordinate system to the one being utilized for the other layers being worked with. After setting spatial reference, press ***OK***.



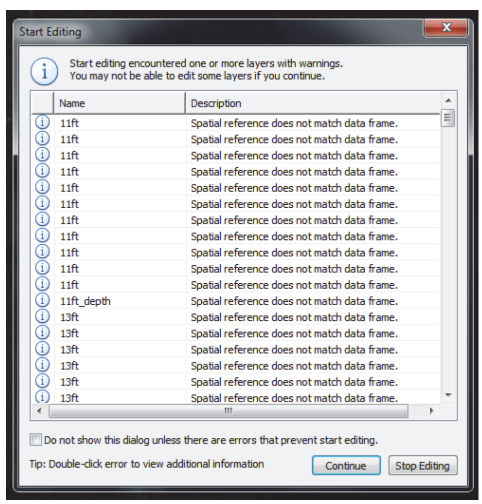
Close **ArcCataolg** and return to **ArcMap**. Activate the ***Editor*** toolbar under ***Customize/Toolbars***.



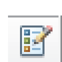
Right click on the created **cloud_cut** layer and select ***Edit Features*** and then ***Start Editing***.



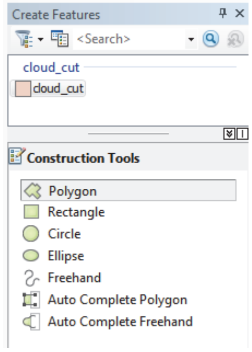
If the following window appears select Continue.



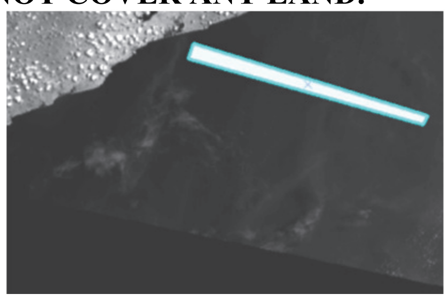
In the ***Editor*** toolbar, press the ***Create Features icon.***



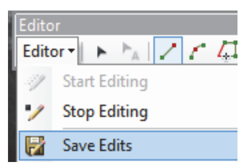
A **Create Features** window will open. Select the "**cloud_cut**" feature and then select ***polygon.***



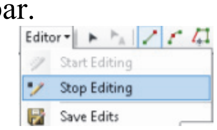
Create a polygon over the infrared layer, which contains both dark sections and bright sections. Create a polygon that is narrow and crosses over the dark areas in the water. To create the polygon, click once to create a vertex point and double click on the last vertex to finish. **MAKE SURE THIS POLYGON DOES NOT COVER ANY LAND.**



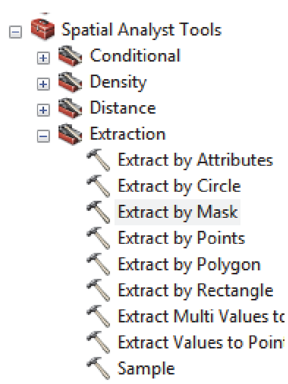
After creating the desired polygon, select ***Save Edits*** in the ***Editor*** toolbar.



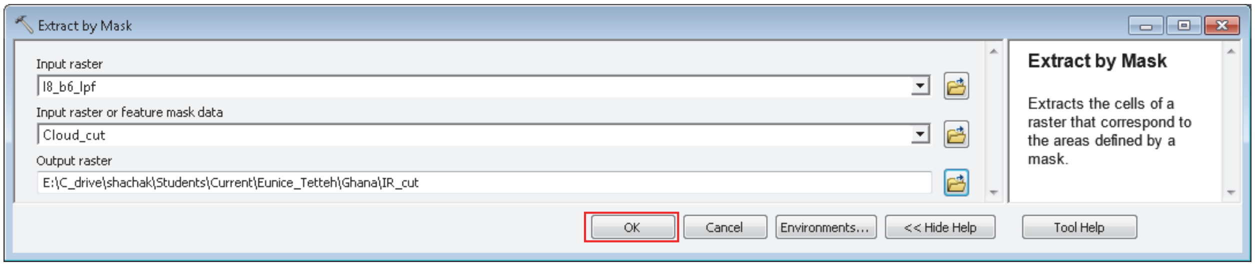
Then select ***Stop Editing*** in the ***Editor*** toolbar.



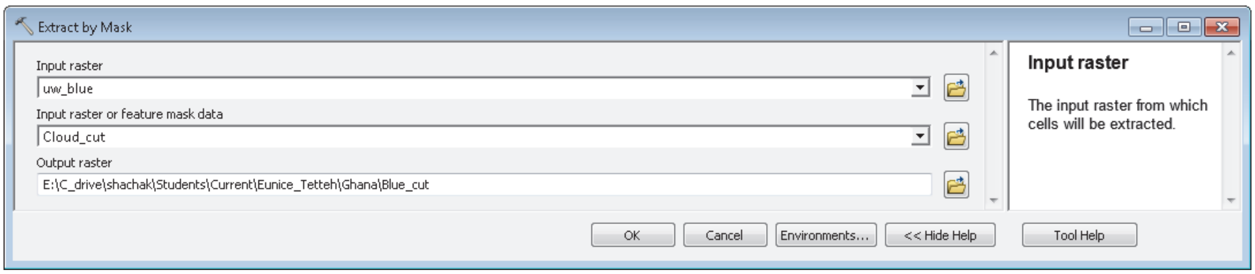
Select **Spatial analyst Tools / Extraction / Extract by Mask** in the **Toolbox** window.

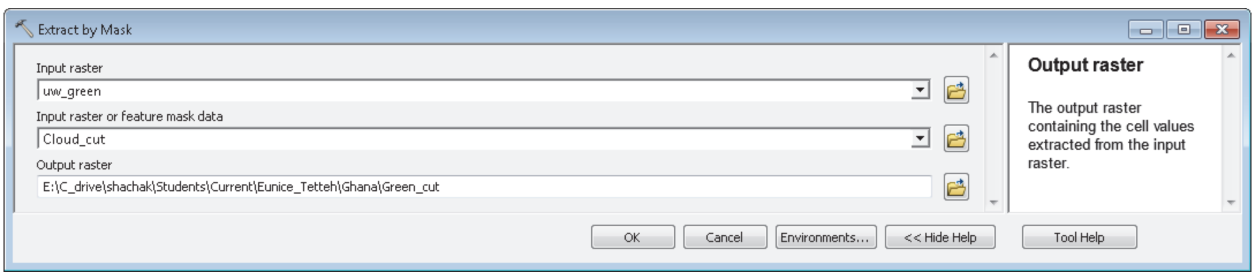


In the **Extract by Mask** window, Input the infrared layer as the raster layer and select ***cloud_cut*** as the mask. Save the output layer as ***IR_cut*** and press ***OK***.

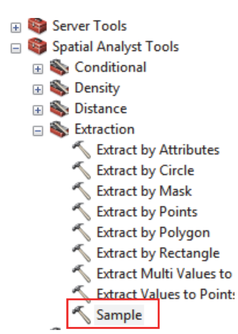


Repeat the ***Extract by Mask*** command with the blue and green layers.

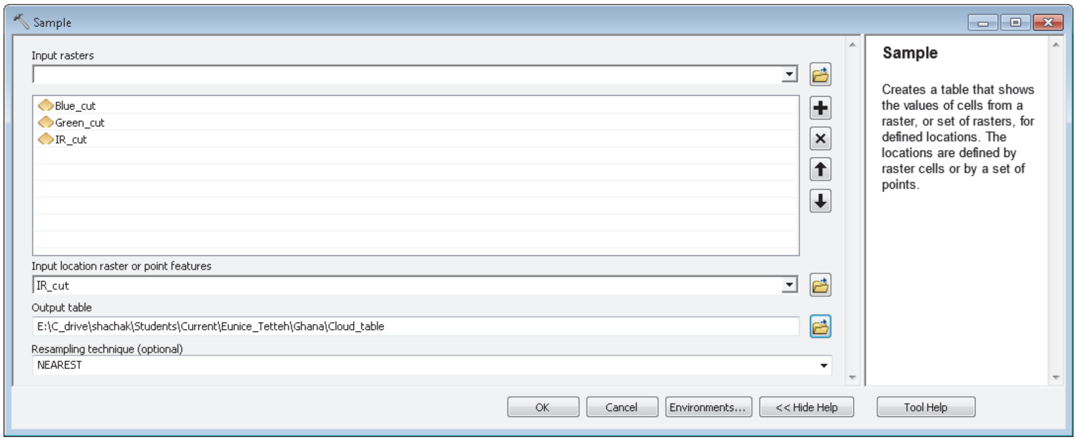




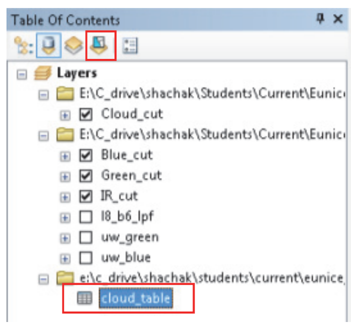
Select **Spatial analyst Tools / Extraction / Sample** in the **Toolbox** window.

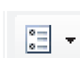


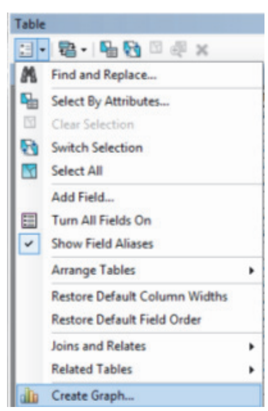
Insert into the **Sample** window the ***Blue_cut, Green_cut,*** and ***IR_cut*** as input rasters. Select the ***IR_cut*** as the input location raster and ***cloud_table*** as the output table. Press ***OK***.



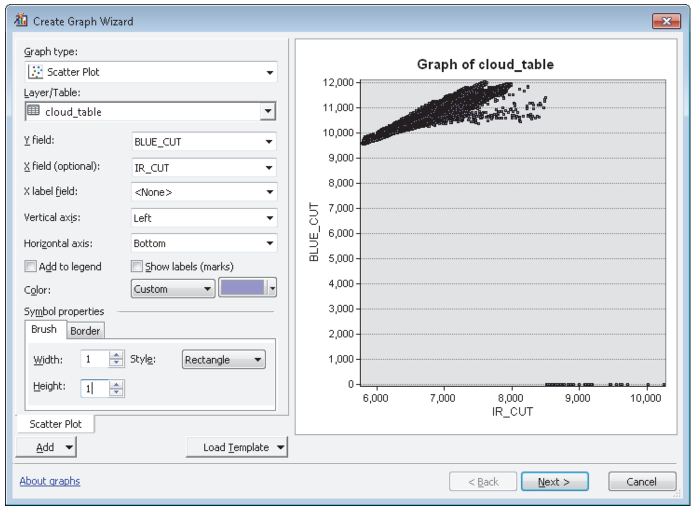
Make sure that your view in the **Table of Contents** is **List by Source** and then open the ***cloud_table*** by right-click on and select ***Open***.



Select the  button in the **Table** window, and select ***Create Graph***.

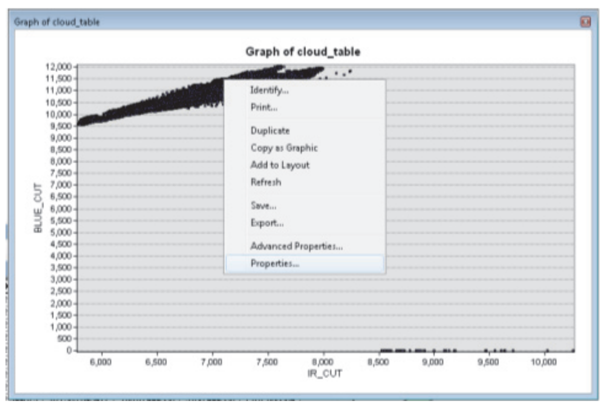


In the **Create Graph Wizard** window, change the graph type to ***Scatter Plot.*** Select ***Blue_cut*** for the Y field and ***IR_cut*** for the X field. Press ***Next >*** and then Press ***Finish.***

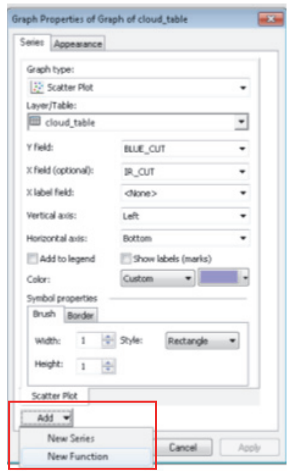


NOTE: It may take the computer more time to respond after each selection due to amount of points in the dataset.

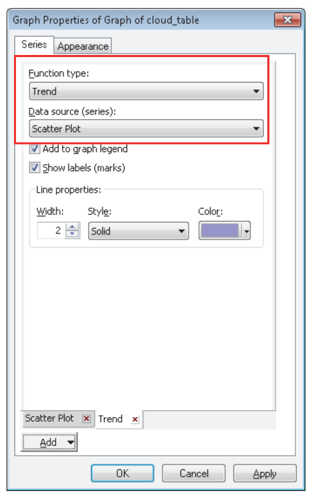
Right click on the graph and select ***Properties...***



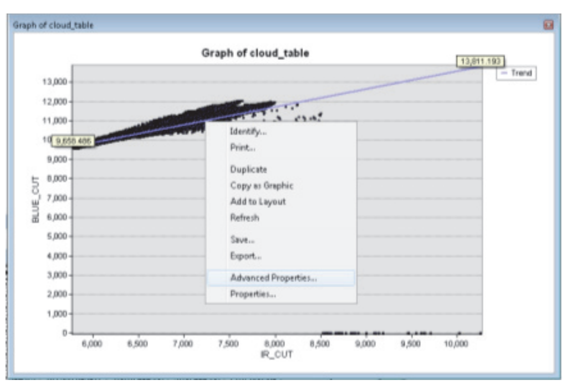
Press the ***Add*** button in the **Graph properties** window and select ***New Function***.



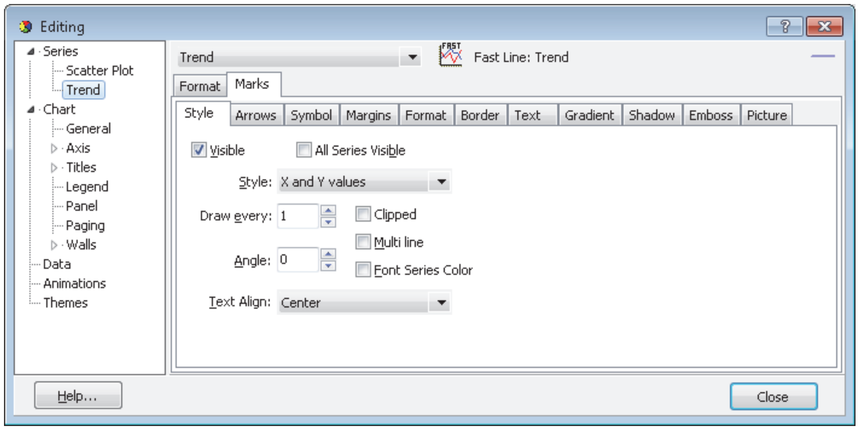
Under the **Series** tab, select ***Scatter Plot*** as the source data and check the ***Show Labels***. Press ***OK***.



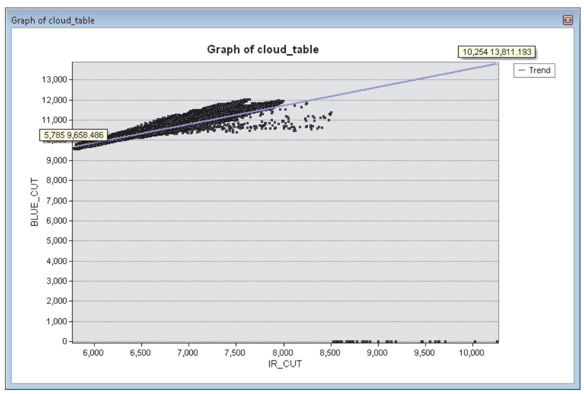
A trend-line and labels have been added to the plot. Right click on the graph and select ***Advanced Properties...***



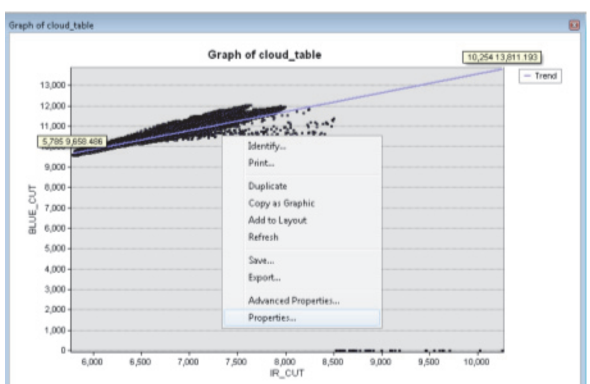
In the Editing window, select Trend and the under the **Mark** tab, select the **Style** tab and change the Style to ***X and Y values***. Press ***Close***.



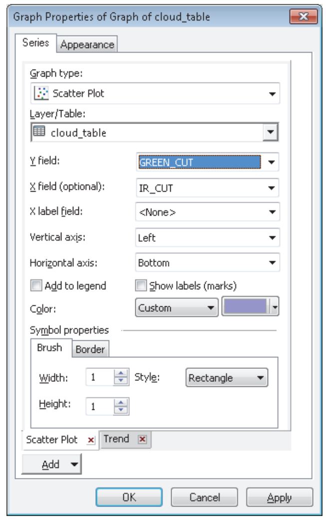
On the graph should be two coordinate points. Record the left point values as the x_1 and y_1 (in this example, x_1=5785 and y_1=9658) and the right point values as the x_2 and y_2 (in this example, x_2=10254 and y_2=13811).



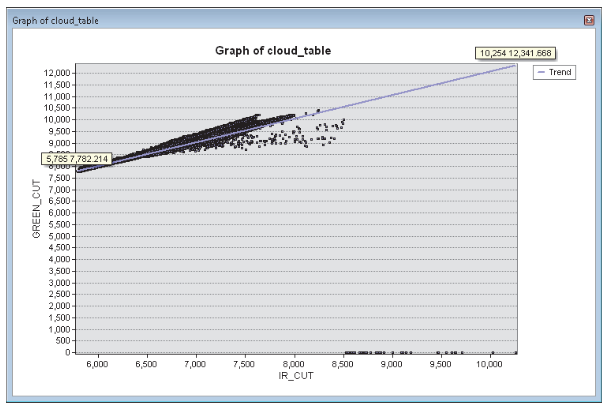
Create a graph and calculate the x_1, y_1, x_2 and y_2 for the ***Green_cut*** layer using the ***IR_cut*** layer. Right click on the graph and select ***Properties...***



On the bottom of the **Graph Properties** window, select the **Scatter Plot** tab. Change the Y field selection to ***Green_cut*** layer using the ***IR_cut*** layer. Press ***OK.***



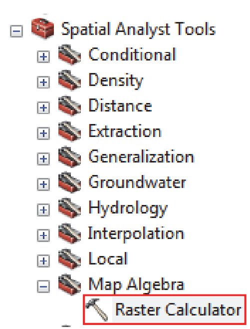
The Y axis graph has been updated to the green band. In this example, y_1=7782 and y_2=12342.



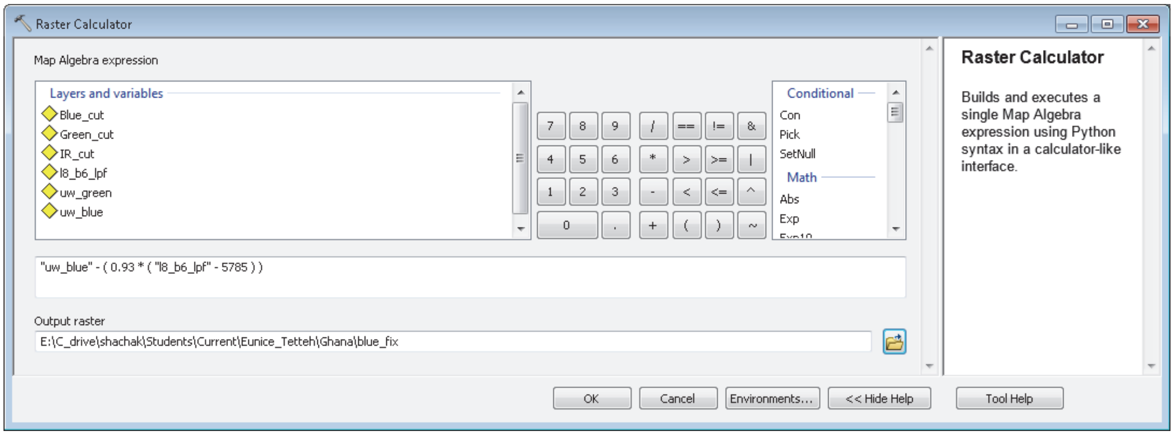
Calculate the slope of the trend for the blue and green layers using the following equation:

$$Slope = \frac{y_2 - y_1}{x_2 - x_1}$$

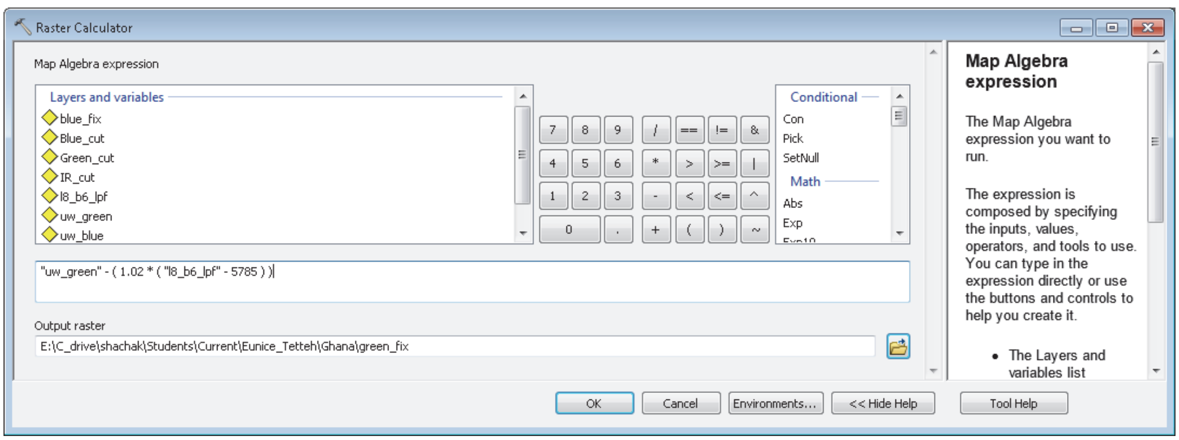
Select **Spatial analyst Tools / Extraction / Raster Calculator** in the **Toolbox** window.



Use the following equation in the raster calculator: ***UW_Blue - Slope * (IR_lpf - X_1).*** For this example (slope blue: 0.93), this should be as follows:



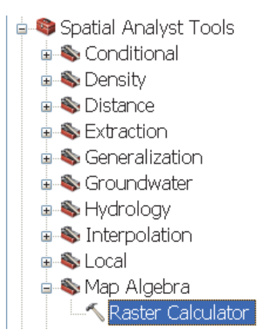
Repeat the calculation for the green band using the following equation: ***UW_Green - Slope * (IR_lpf - X_1).*** In this example (slope blue: 1.02):



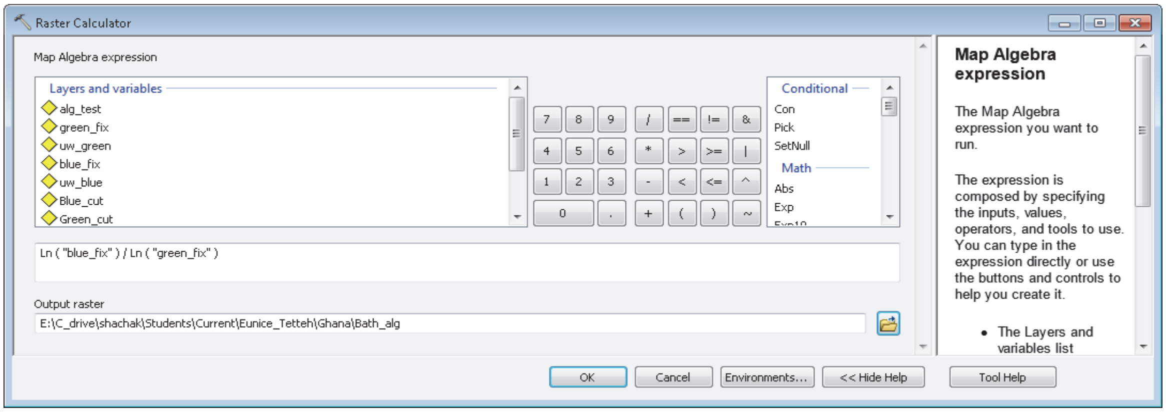
The result will be radiometrically corrected blue and green bands.

A.6 Applying the Bathymetry Algorithm

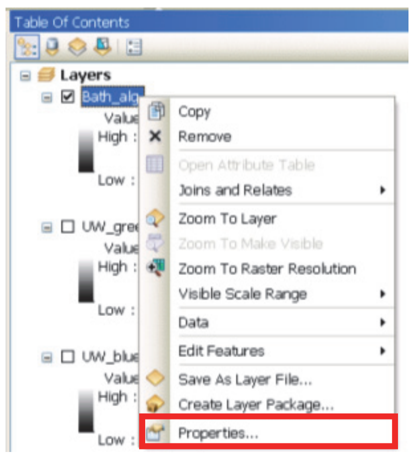
Select **Spatial analyst Tools / Map Algebra / Raster Calculator** in the **Toolbox** window.



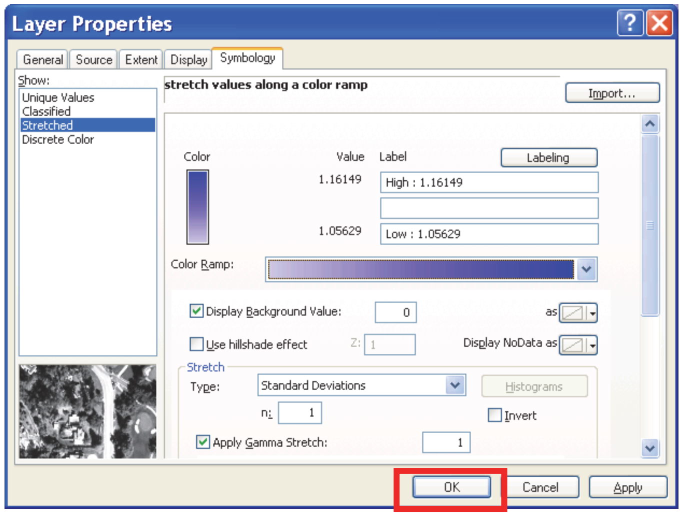
In the Raster Calculator window, write the following command: Ln ("blue_fix") / Ln ("green_fix")



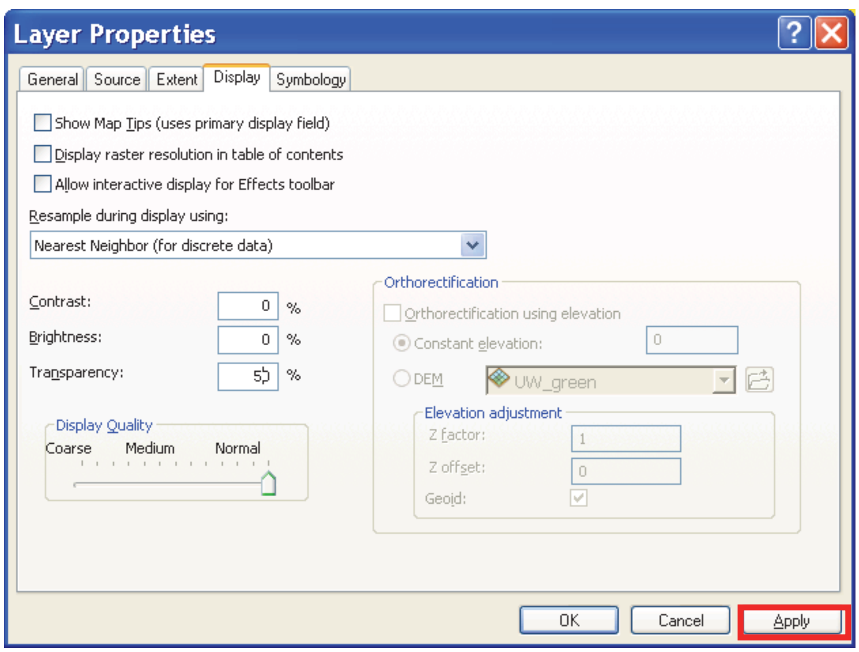
For visual inspection, zoom in to an area of interest (in shallow waters). Select the layer ***properties*** from the **Table of Contents**.



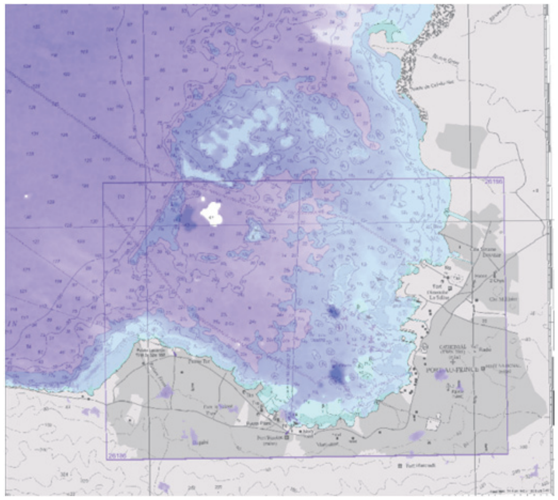
In the **Layer Properties** window under the **Symbology** tab, set the **color ramp** and **Apply Gamma Stretch: From Current Display Extent** as follows and press **Apply.**



In the **Layer Properties** window under the **Display** tab, set the **Transparency** to **50%** and press OK.



It is now possible to compare the algorithm results with the chart.



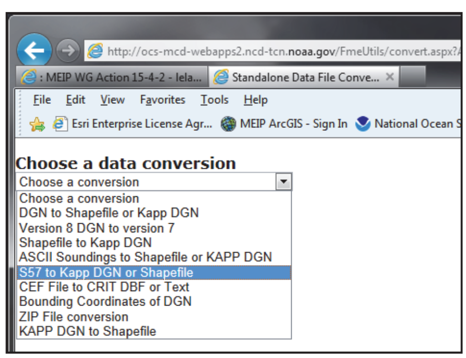
A.7 Vertical Referencing and Depth of Extinction Calculation

NOTE: There are two options for referencing the algorithm result to the chart datum: 1) referencing using S-57 attributes from an ENC, or 2) manually calculating the gain and offset using a raster chart. It is recommended to use option 1 when possible, as it provides a fast and accurate solution. The sounding files from an ENC are equivalent to a point shapefile that. As by product of the referencing procedure, the effective depth of the bathymetry (i.e., depth of extinction) is calculated.

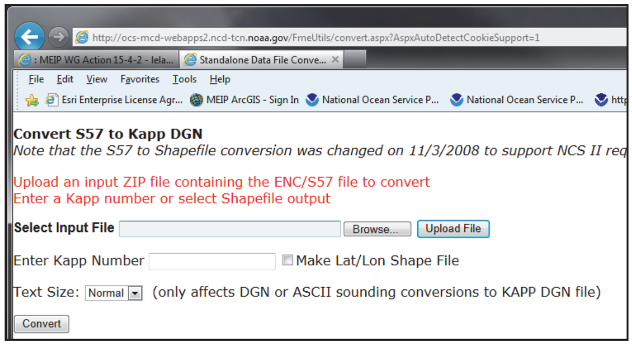
A.7.1 Exporting S-57 Attributes into Shapefiles

NOTE: This step is an internal NOAA/NOS/OCS/MCD procedure. If the S-57 attributes are already provided to you as a shapefile, proceed to the next section.

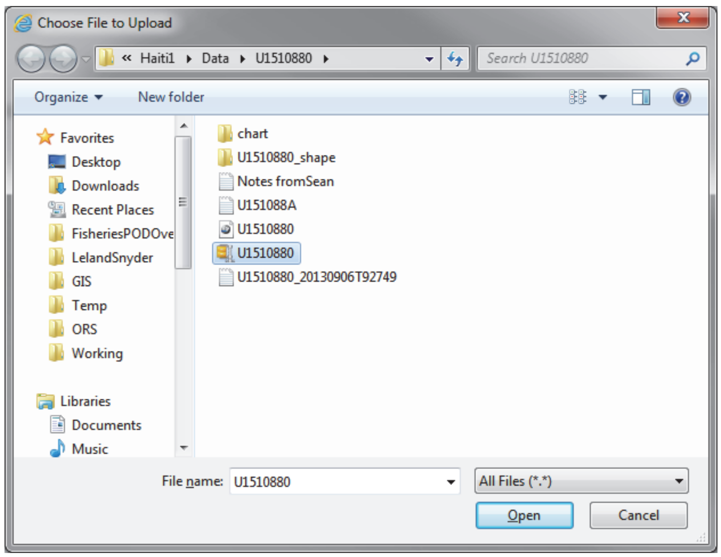
Open the **FME Standalone (Data File) Convertor** by typing http://ocs-mcd-webapps2.ncd-tcn.noaa.gov/FmeUtils/convert.aspx.gov in the NOAA internal web browser. In this window, select: ***S57 to Kapp DGN or Shapefile***.



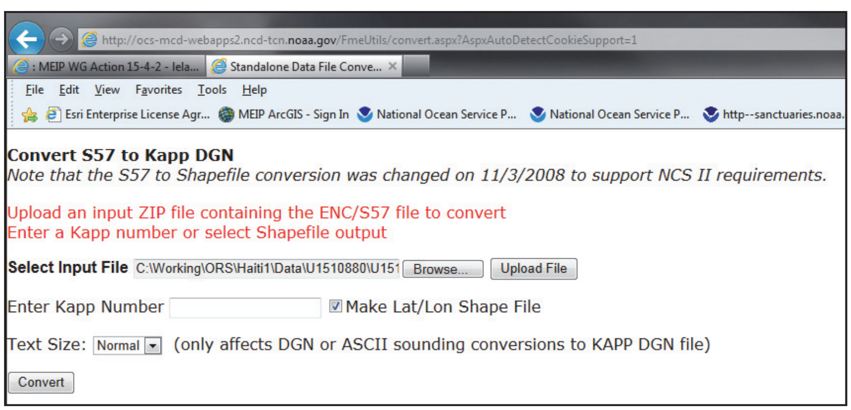
The screen will change as follows:



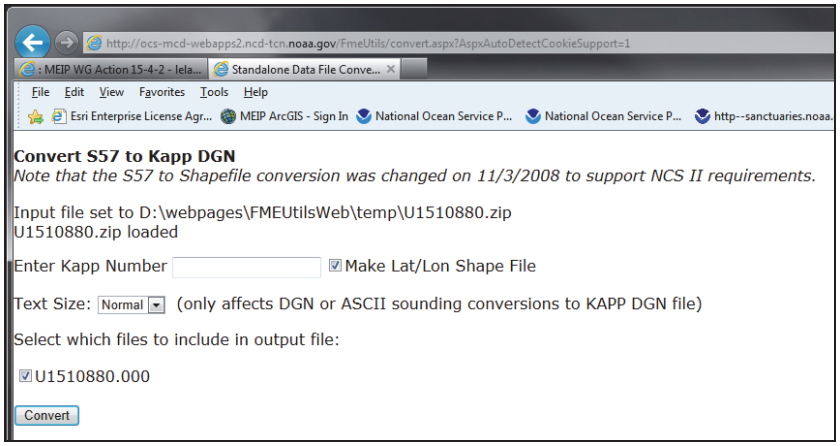
Click on the ***Browse...*** button and select the "***.zip.000**" file



Check the ***Make Lat/Lon Shapefile*** and press the ***Upload File Button.***

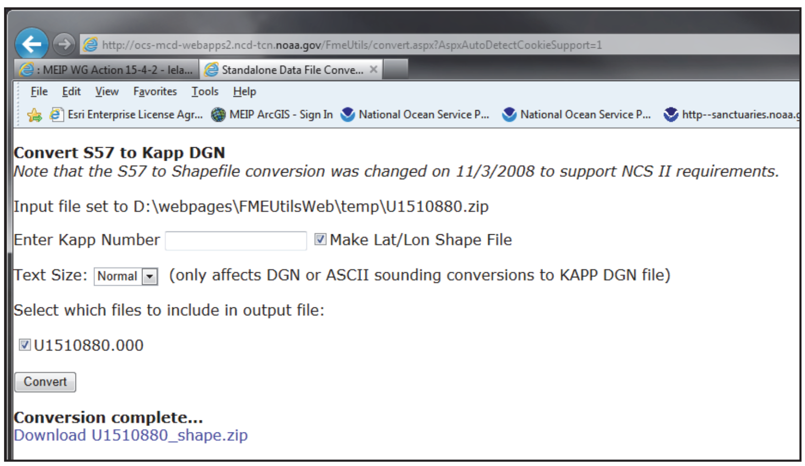


You will receive a notice that *.000 has been zipped for upload. Press ***Convert***.

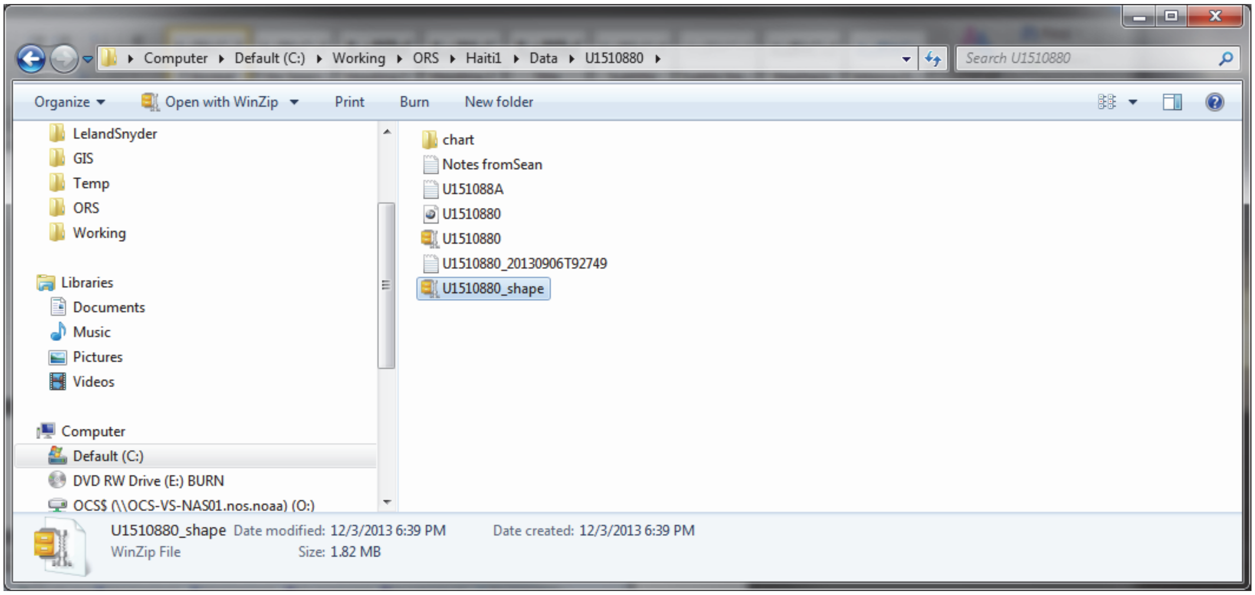


You will receive a notice that "**Conversion is complete**". You can close the web browser and open a Windows explorer.

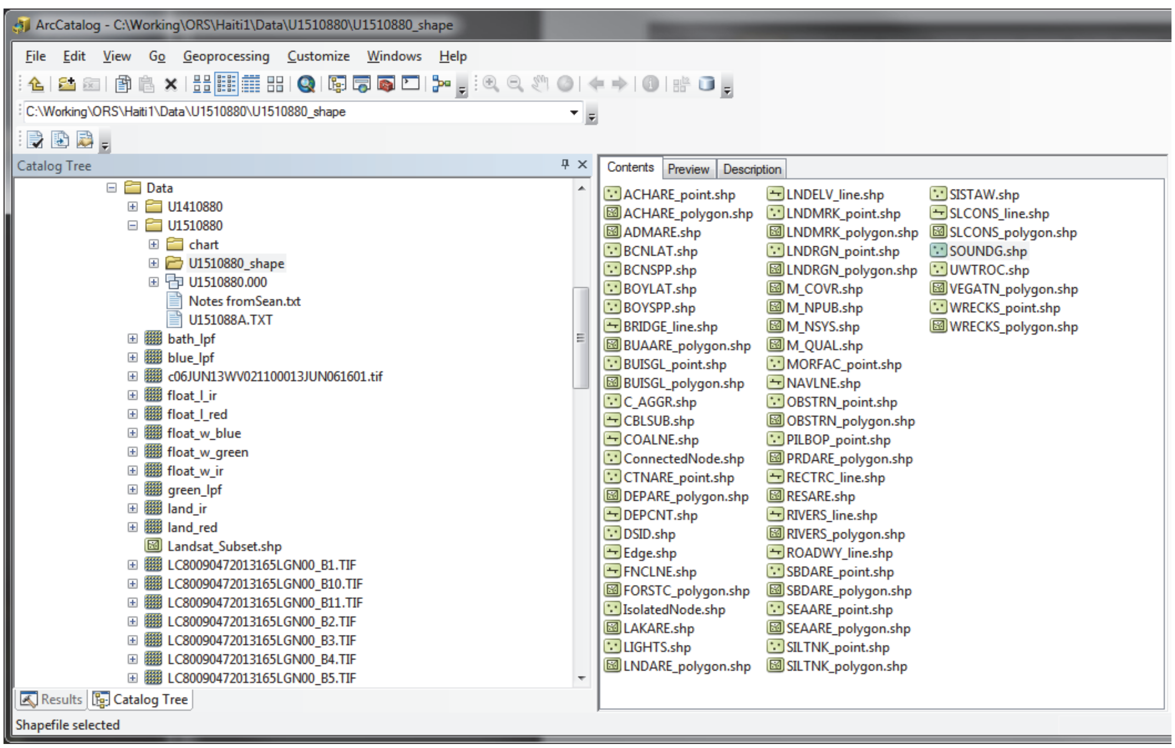
Note: The file is zipped.



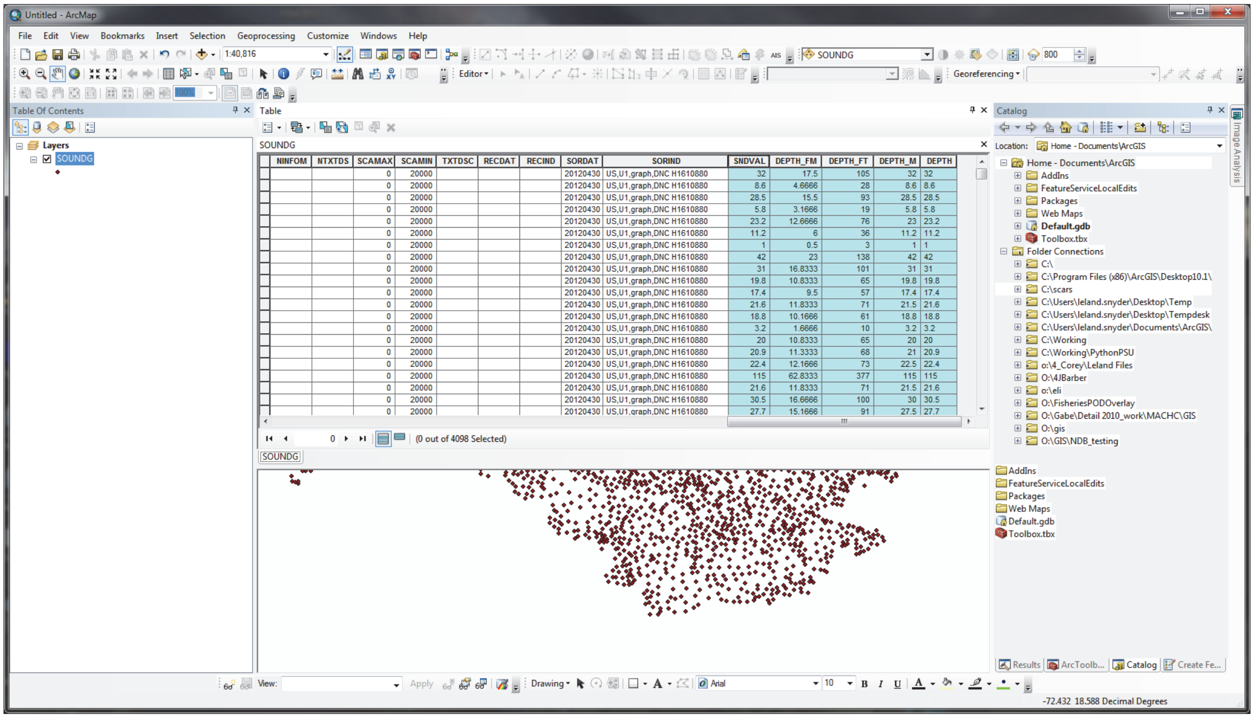
Select the new file and unzip it.



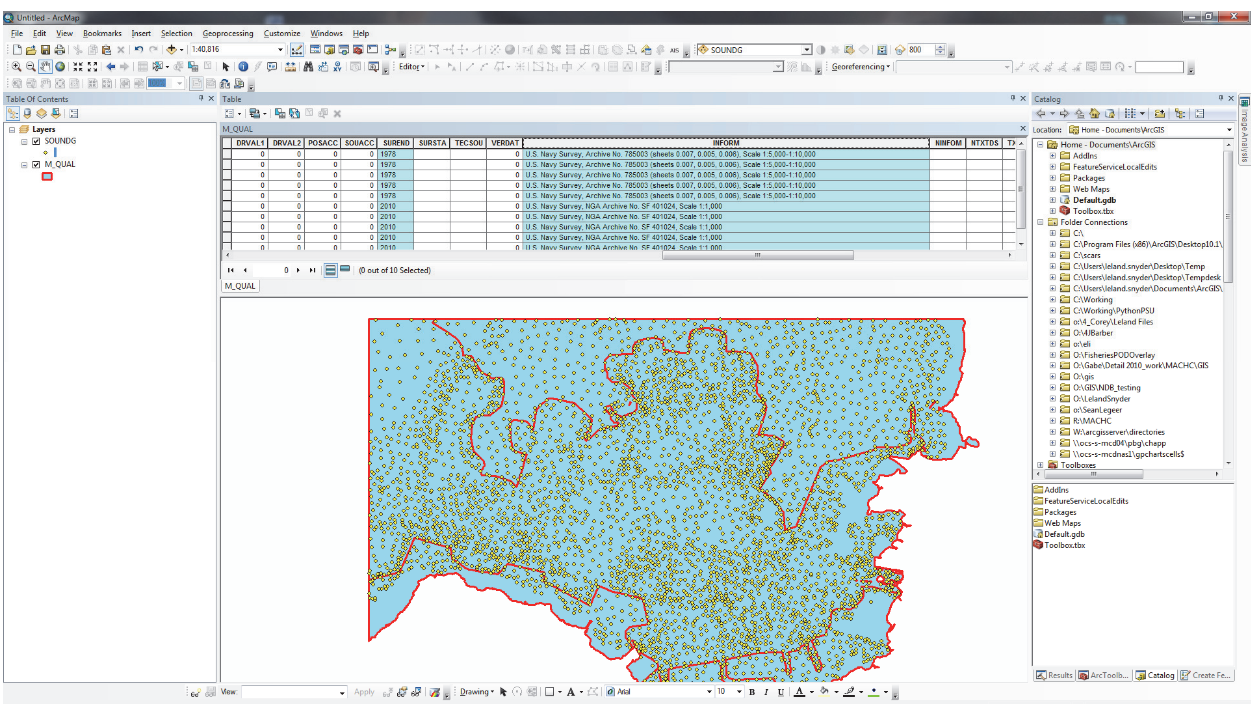
Open ArcMap and ArcCatalog to invetigate the files.



SOUNDG (Sounding point shapefile): In the attribute table, the **DEPTH_FM** field contains the chart soundings in fathoms, the **DEPTH_FT** field contains the chart soundings in feet, and the **DEPTH_M** field contains the chart soundings in meters.

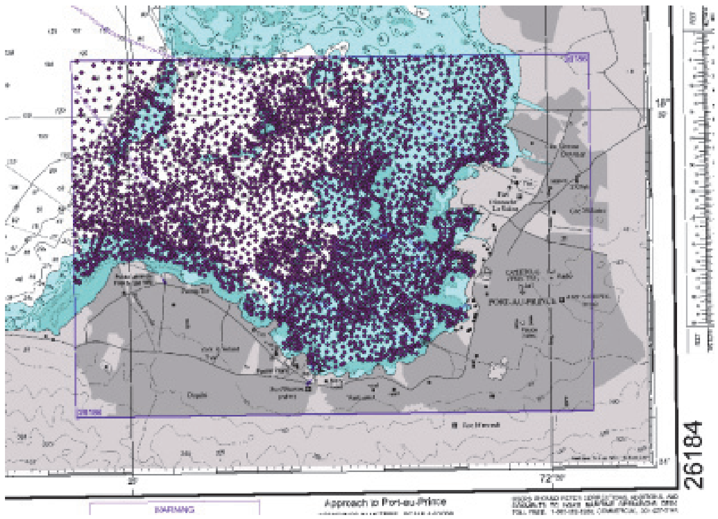


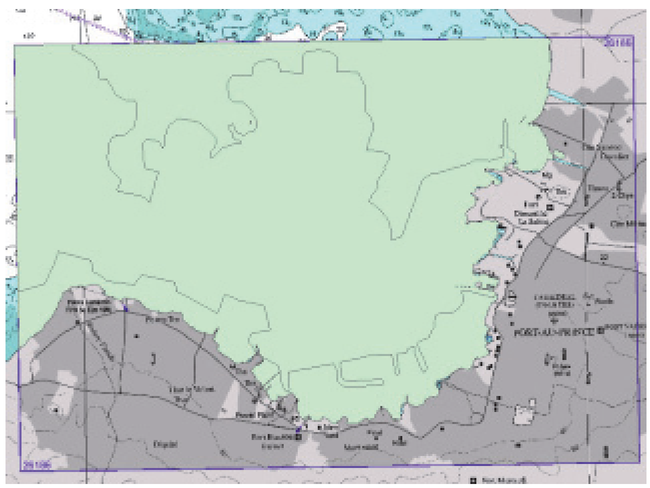
M_QUAL (Source diagram polygon shapefile): In the attribute table, the **SUREND** field contains the year of the survey and the **INFORM** field contain the full survey details.



A.7.2 Preparing the S-57 Attributes

Use **Add Data** to add the SOUNDG point feature and M_QUAL polygon feature data in ArcMap.

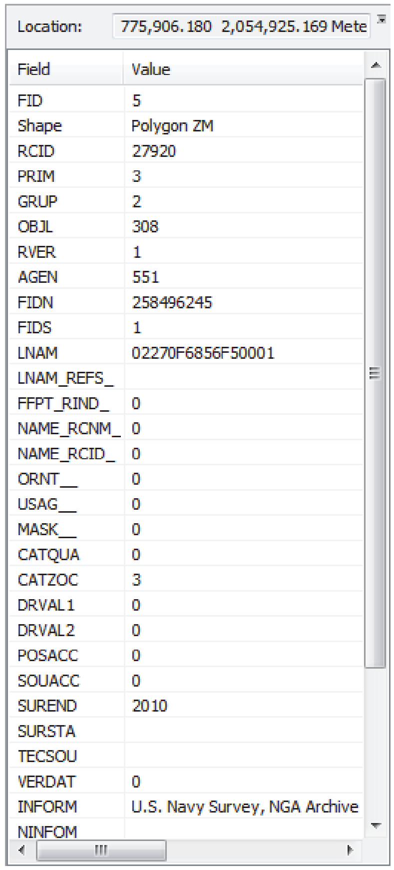




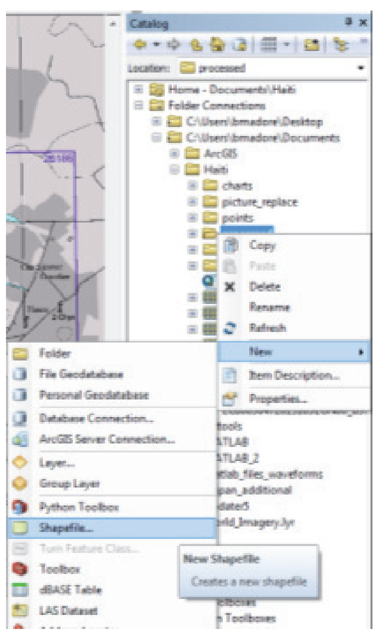
Note: make sure to have the algorithm result turned on to verify similarity to the chart soundings.

To determine when each area was surveyed select the **Identify** tool and select a region.

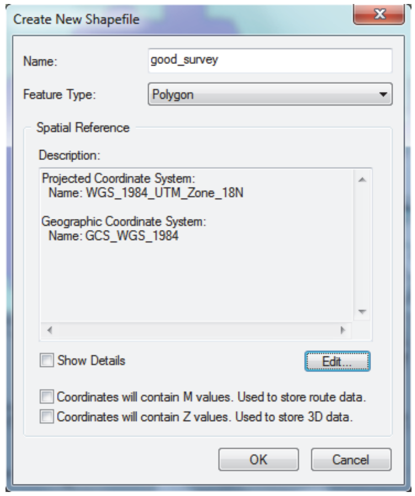
The SUREND number is the year of the survey (In this case, the 2010 data (the most recent) is the only data that will be used to calculate the bathymetry).



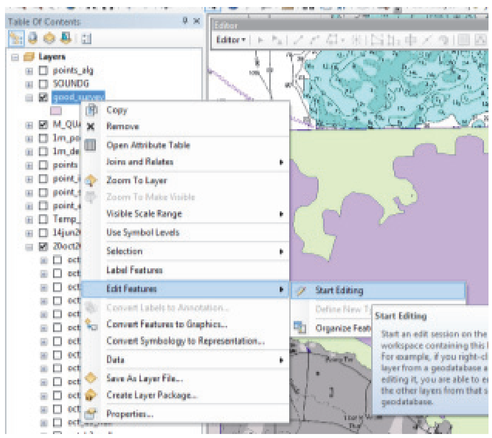
Open the **Catalog** and select a folder to save a new shapefile to, right-click the folder and select **New** then **Shapefile**.



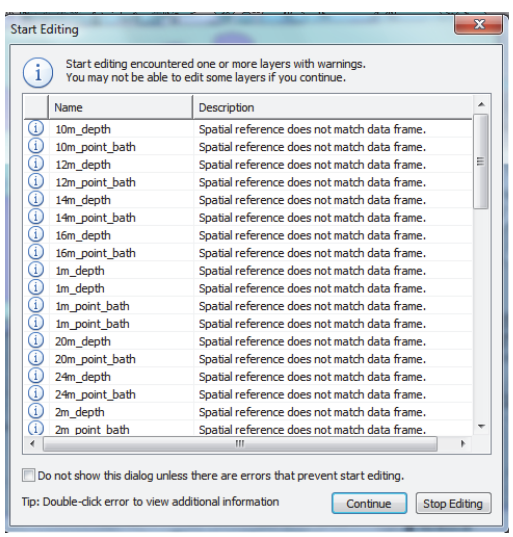
Name the file **good_survey**, select **Polygon** as the feature type and select **Edit** to choose the appropriate coordinate system.



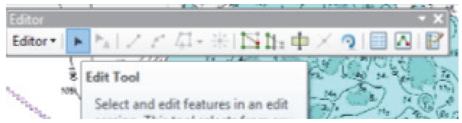
Right-click the good_survey layer or the survey quality layer being used and select **Edit Features** then **Start Editing.**



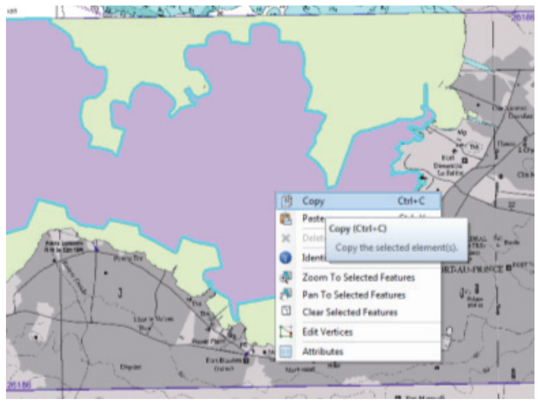
Select **Continue** if the following window appears.



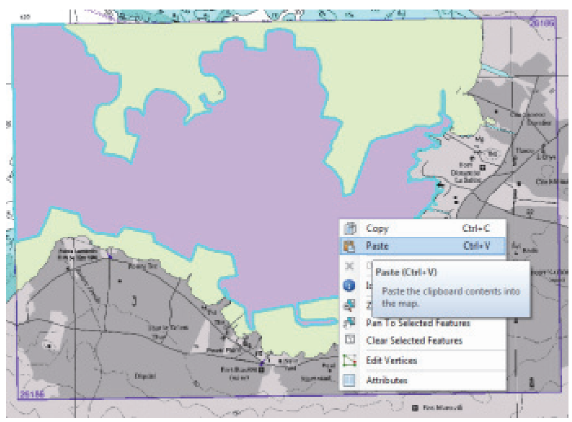
Select the **Edit Tool** in the Editor toolbar.



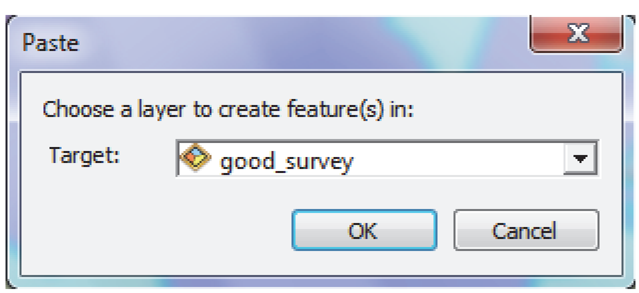
Select the most recently surveyed regions on the survey quality shapefile (M_QUAL). It is possible to select multiple polygons that have good survey data, by holding the **shift** key to select multiple regions at the same time. Once selected, right-click the highlighted areas and select **Copy.**



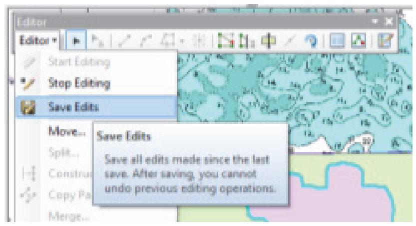
Then right-click and select **Paste.**



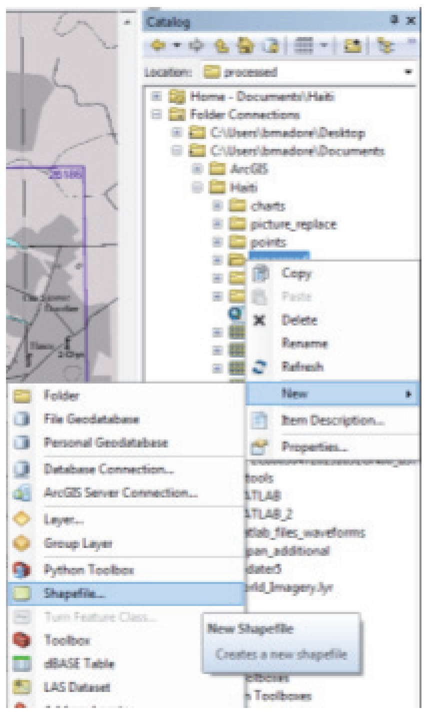
A window will open and select the target layer as the good_survey layer which was recently created.



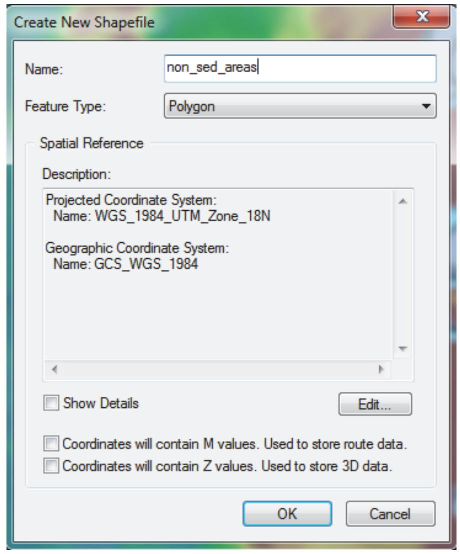
In the **Editor** toolbar, select **Save Edits** and then select **Stop Editing**. The good_survey shapefile will contain only has the regions associated with the most recent surveys.



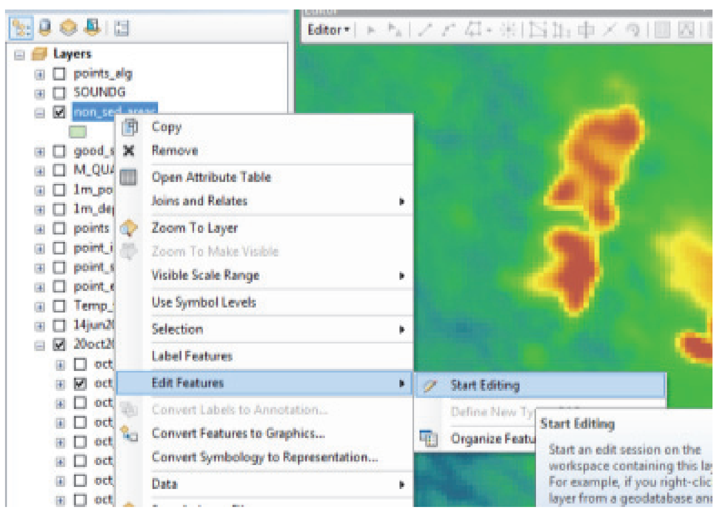
In order to eliminate areas that contain sediment turbulence, another polygon will be created based on a visual inspection of the algorithm layer. In the **Catalog,** select a folder to save a new shapefile to, right-click the folder and select **New** then **Shapefile**.



Name the file "non_sed_areas", select **Polygon** as the feature type, and select **Edit** to choose the coordinate system.

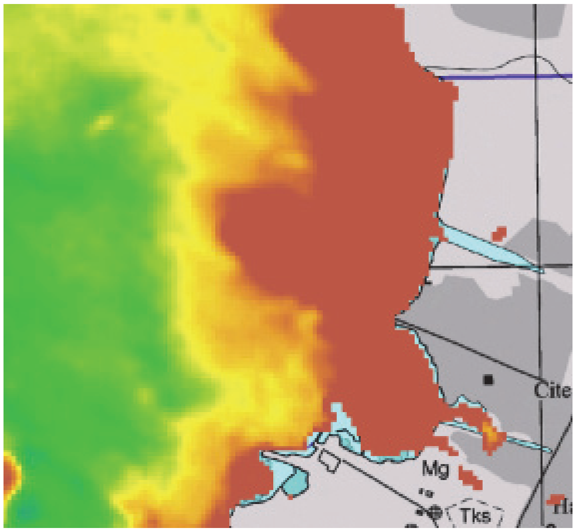


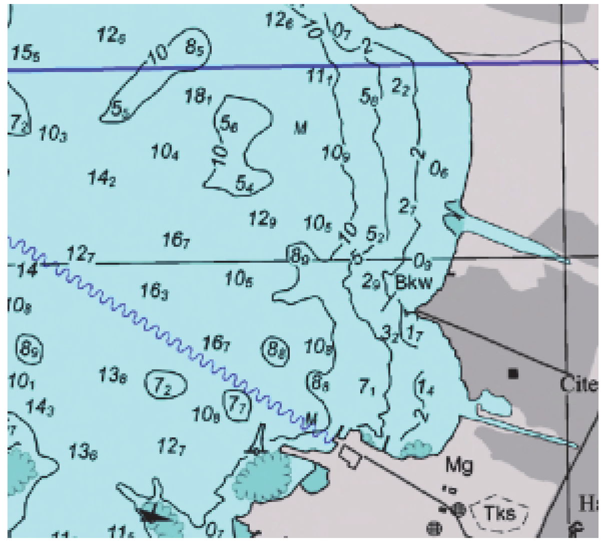
Right-click the non_sed_areas layer and select **Edit Features** then **Start Editing**.



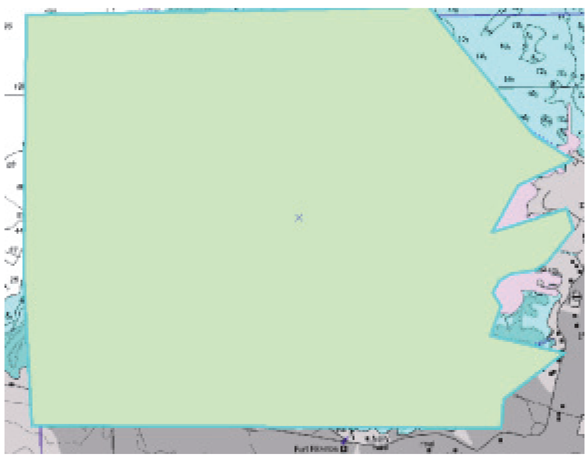
Digitize the areas considered clean from sediment plumes by: 1) selecting the **Create Features** window, 2) selecting the non_sed_areas layer and 3) choosing **Polygon** for the construction tool. Before creating the polygon look at chart soundings near the coast line and the results of the algorithm. Even though the algorithm is not in actual depth units (e.g., feet or meters), it still shows relative depth. Areas that appear more shallow then the chart suggests should not be selected with the polygon.

The following area shows an example of where the algorithm is too shallow, due to sediment in the water column. The red area extends further from shore than would be expected, and the chart supports this as the outer reaches of the red area should not be there at 12 m depth.

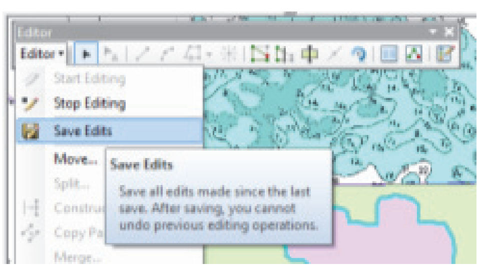




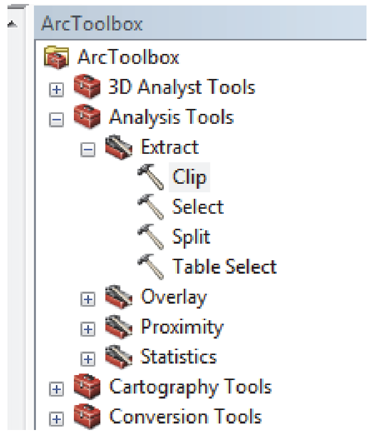
After visually determining the area, create a polygon by selecting the vertices around the clean area.



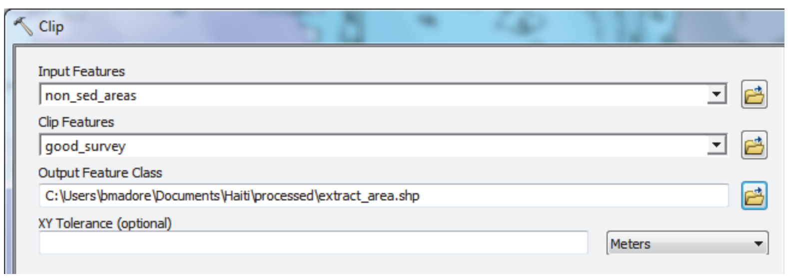
In the **Editor** toolbar, select **Save Edits** and then select **Stop Editing**. The "non_sed_area" shapefile is now associated only with the regions without sediments in the water column.



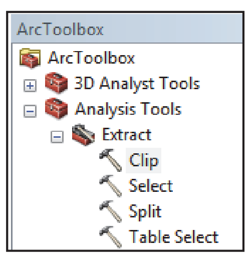
In **ArcToolbox** select **Analysis Tools / Extract / Clip**



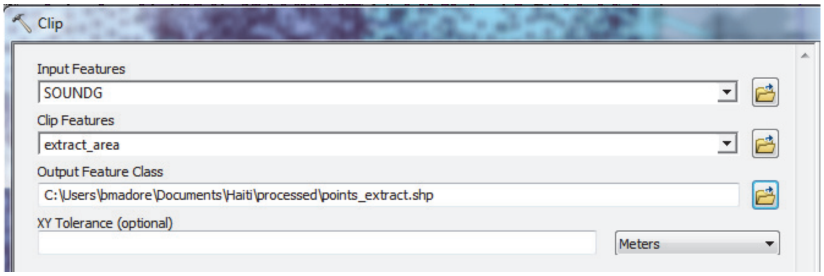
For the **Input Features** select "non_sed_areas" and for **Clip Features** select "good_survey". Choose a location to save the file and save it as "extract_area". This file is the intersection polygon between the most recent survey and the area that was digitized based on a visual inspection (no sediment plumes).



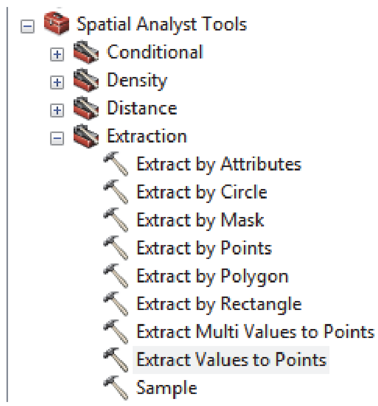
In **ArcToolbox** select **Analysis Tools / Extract / Clip**



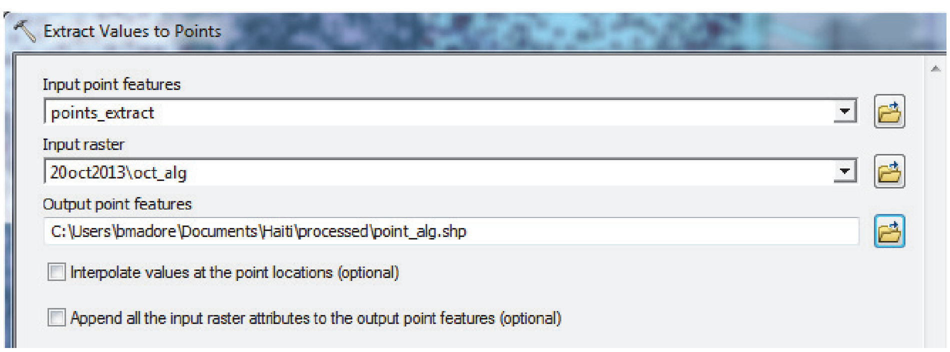
For the **Input Features** select the point feature file (SOUNDG) that was added and for the **Clip Features** select "extract_area". Save the file as "points_extract".



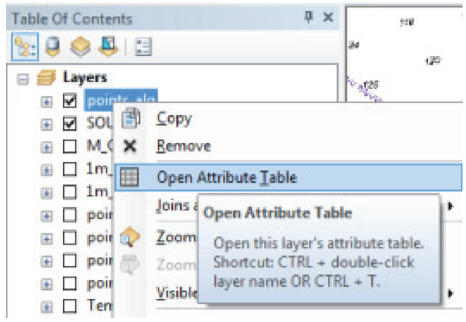
In **ArcToolbox** select **Spatial Analyst Tools / Extraction / Extract Values to Points.** This function will allows sampling of the algorithm results based on the point feature ("point_extract").



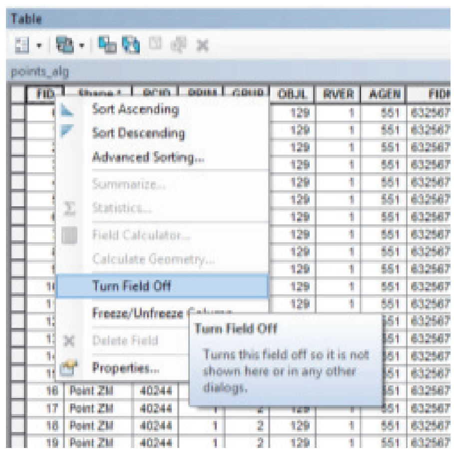
Select the "points_extract" for **Input Point Features**. Input the algorithm results into **Input Raster** and select a destination to save the file, and save it as "point_alg".



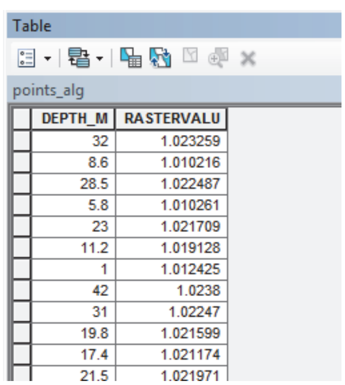
Right-click the "point_alg" feature and select **Open Attribute Table**.



Turn the field off for every column of data except the depth measurements in meters (DEPTH_M) and the algorithm results column (RASTERVALU). To turn a field off, right-click on the label for the column you want to eliminate and select **Turn Field Off**.

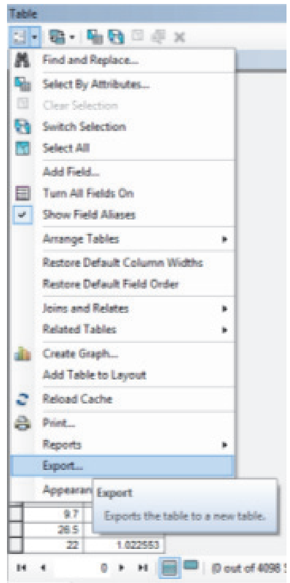


Repeat this until only the depth column and the RASTERVALU column are the only two remaining.

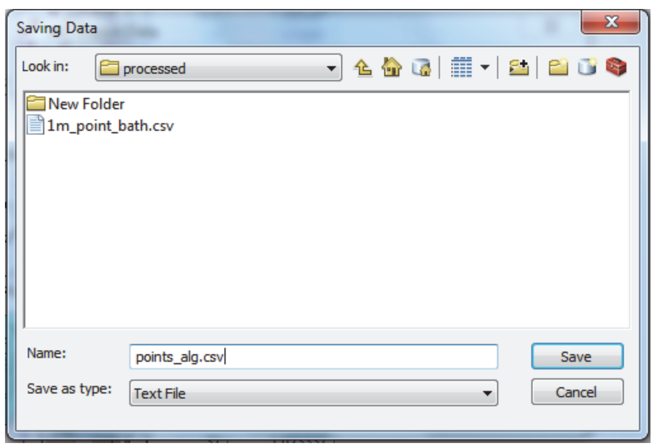


DEPTH_M	RASTERVALU
32	1.023259
8.6	1.010216
28.5	1.022487
5.8	1.010261
23	1.021709
11.2	1.019128
1	1.012425
42	1.0238
31	1.02247
19.8	1.021599
17.4	1.021174
21.5	1.021971

Open the **Table Options** and select **Export.**



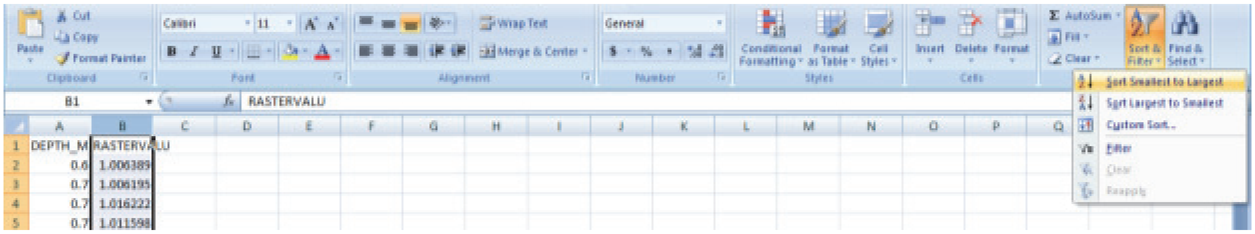
Select a destination folder to save the exported data. When saving select Save type as: **Text File** and save the file as "points_alg.csv". Make sure to save the file with the extension of *.csv.



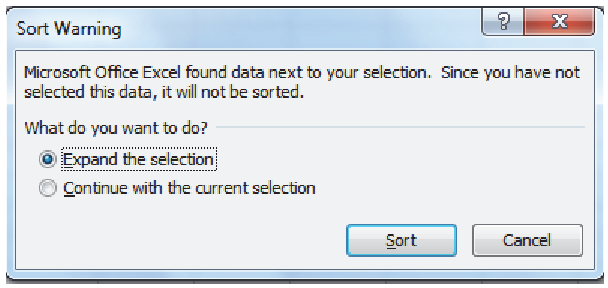
Select **No** when it asks to add the new table to the current map.

A.7.3 Calculating Extinction Depth, Gain and Offset

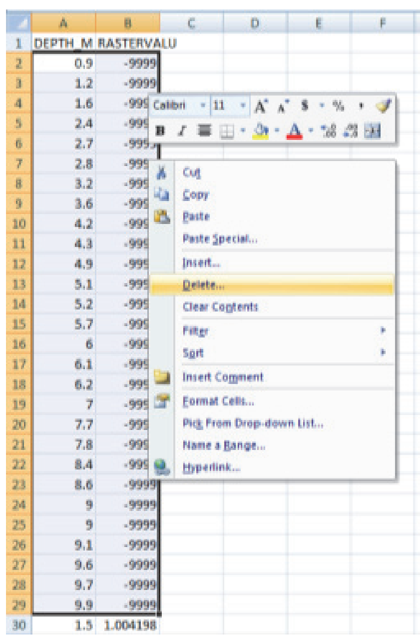
Open the saved "points_alg.csv" file in MS Excel. There will be two columns of data: 1) depth soundings and 2) corresponding algorithm result. Select the B column with the algorithm results and sort it from the lowest to highest by selecting **Sort and Filter**.



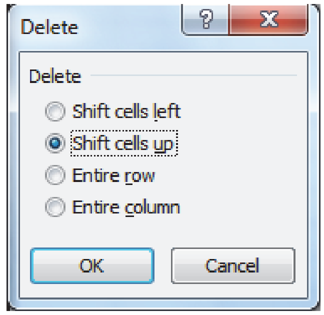
When the sort warning appears, select **Expand Selection**.



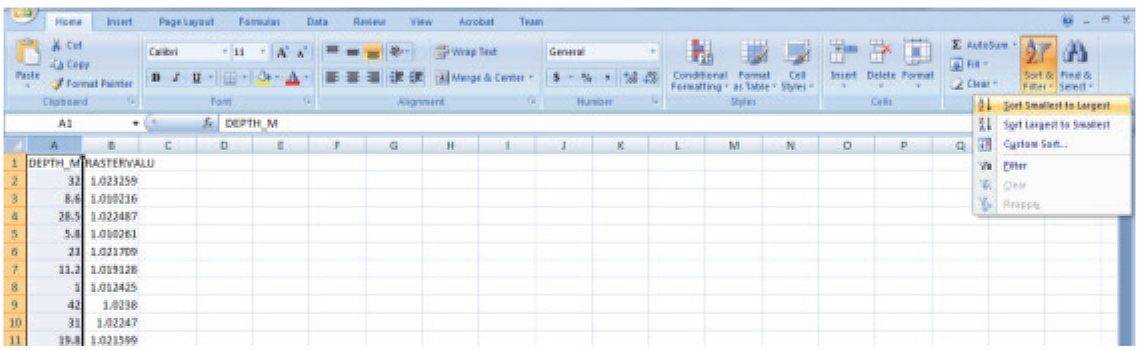
The lowest values in the algorithm result column will appear as -9999. These null values should be deleted. For each -9999, select both the A column value and the B column value then right-click and select **Delete.**



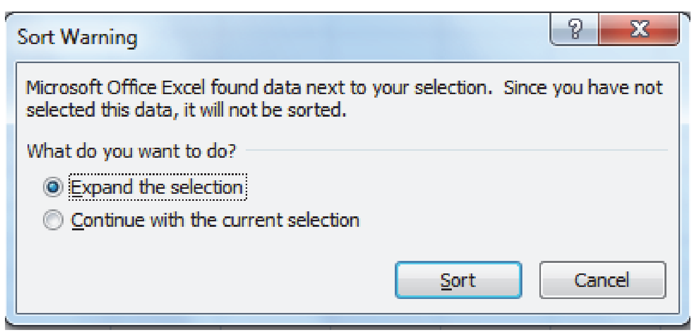
When the **Delete** window appears, select ***Shift cells up*** and press ***OK***.



Select column A and select **Sort Smallest to Largest** in the **Sort and Filter** tool. Make sure the values in column A have been sorted from smallest to largest.

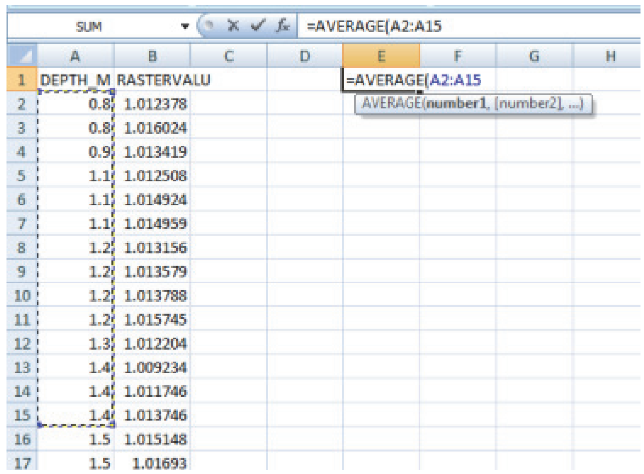


When the **Sort Warning** appears, select **Expand Selection**.



The data will be plotted at 1-m interval water depths (i.e., 0.5 m to 1.4 m, 1.5 to 2.4 m, ...). To do this write "=**Average(**" into cell E1. Highlight in Column A all depths between .5 m and 1.4 m and press Enter. Repeat this process in E2 to average the depths ranging between 1.5 m and 2.4 m. Continue this process until you have reached at least 15 m.

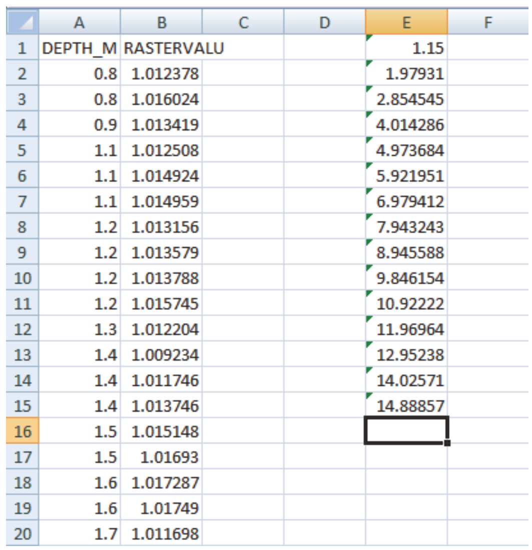
Note: If you collected the soundings manually, continue here.



SUM =AVERAGE(A2:A15

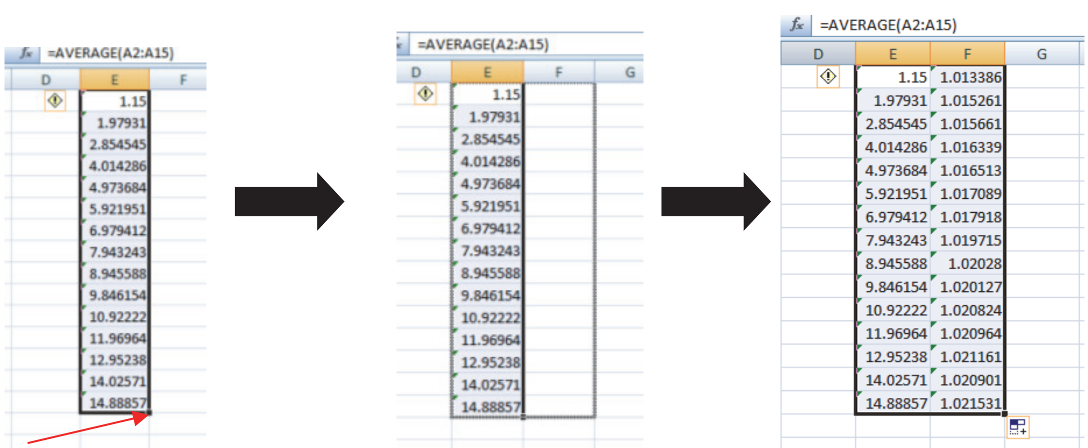
	A	B	C	D	E	F	G	H
1	DEPTH_M	RASTERVALU			=AVERAGE(A2:A15			
2	0.8	1.012378			AVERAGE(number1, [number2], ...)			
3	0.8	1.016024						
4	0.9	1.013419						
5	1.1	1.012508						
6	1.1	1.014924						
7	1.1	1.014959						
8	1.2	1.013156						
9	1.2	1.013579						
10	1.2	1.013788						
11	1.2	1.015745						
12	1.3	1.012204						
13	1.4	1.009234						
14	1.4	1.011746						
15	1.4	1.013746						
16	1.5	1.015148						
17	1.5	1.01693						

You end result (for water depth of 15 m), should look as follows:



	A	B	C	D	E	F
1	DEPTH_M	RASTERVALU			1.15	
2	0.8	1.012378			1.97931	
3	0.8	1.016024			2.854545	
4	0.9	1.013419			4.014286	
5	1.1	1.012508			4.973684	
6	1.1	1.014924			5.921951	
7	1.1	1.014959			6.979412	
8	1.2	1.013156			7.943243	
9	1.2	1.013579			8.945588	
10	1.2	1.013788			9.846154	
11	1.2	1.015745			10.92222	
12	1.3	1.012204			11.96964	
13	1.4	1.009234			12.95238	
14	1.4	1.011746			14.02571	
15	1.4	1.013746			14.88857	
16	1.5	1.015148				
17	1.5	1.01693				
18	1.6	1.017287				
19	1.6	1.01749				
20	1.7	1.011698				

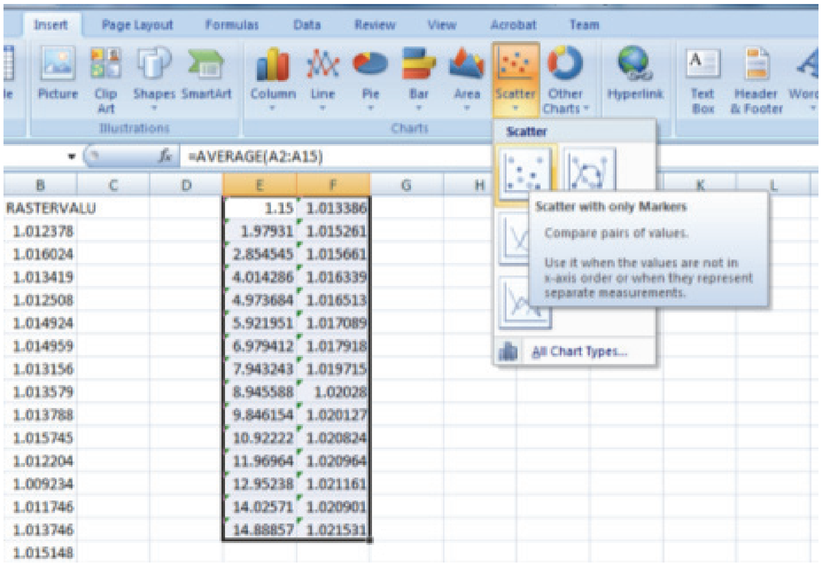
Highlight only the values in the E column and select the box in the lower right corner. Drag the box over one row.



=AVERAGE(A2:A15)

E	F
1.15	1.013386
1.97931	1.015261
2.854545	1.015661
4.014286	1.016339
4.973684	1.016513
5.921951	1.017089
6.979412	1.017918
7.943243	1.019715
8.945588	1.02028
9.846154	1.020127
10.92222	1.020824
11.96964	1.020964
12.95238	1.021161
14.02571	1.020901
14.88857	1.021531

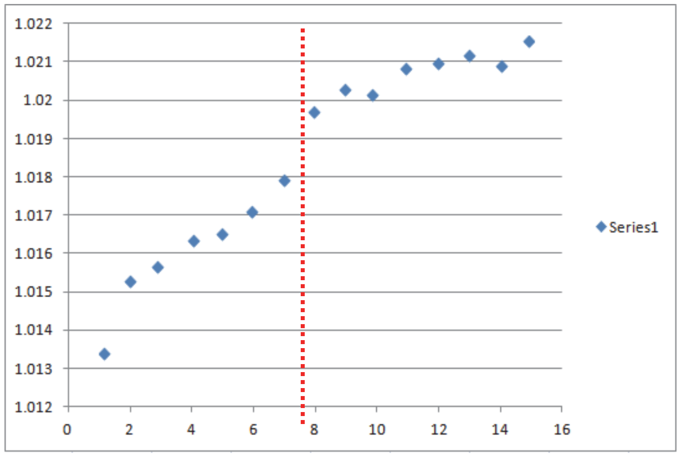
The values created in the F column are the average values from the algorithm results that correspond to the appropriate averaged depth value. Select columns E and F and select **Scatter with only Markers** in the **Insert** tab.



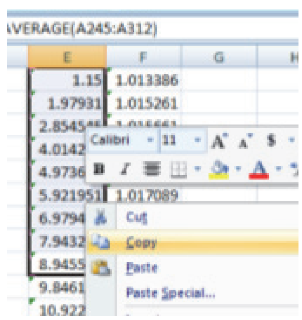
The resulting graph will show a linear line at the lower depths and a break (shoulder).

<u>**Note 1**</u>: The break represents the extinction depth, which is around 9 meters in our case. Typically, beyond this depth there is a change in angle and/or there is less correlation between the sounding and the algorithm values.

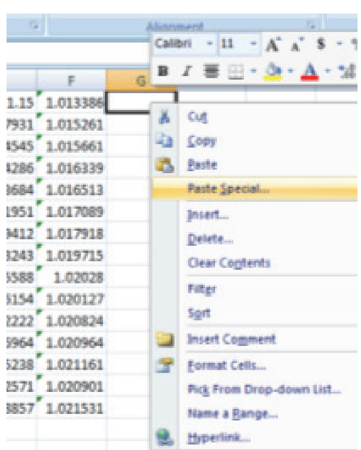
<u>**Note 2**</u>: If there is no break in the plot, it is recommended to extend the depth range. Extinction depths in the Caribbean can reach up to 30 in clear water days away from ports and marine traffic.



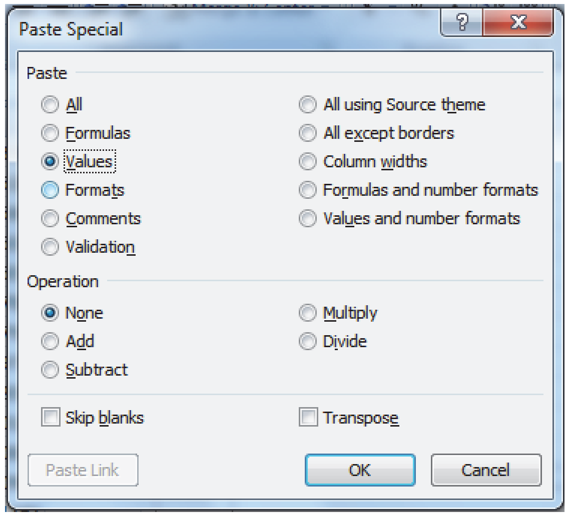
The linear section of the results (up to the break) will be used to determine the gain and offset for referencing the algorithm layer in ArcMap. In order to do that, subset the dataset by selecting the depths in column E that are shallower than the break. Right-click and select **Copy**.



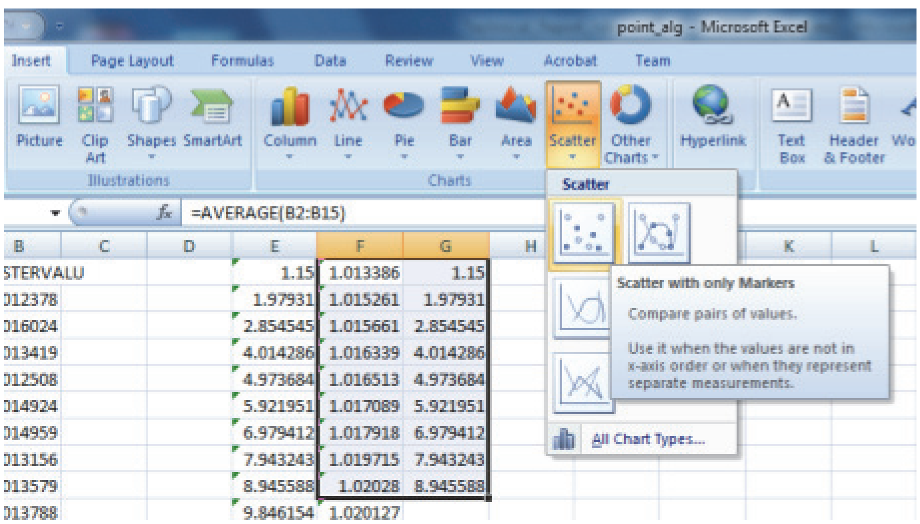
Right-click in cell G1 and select **Paste Special...**.



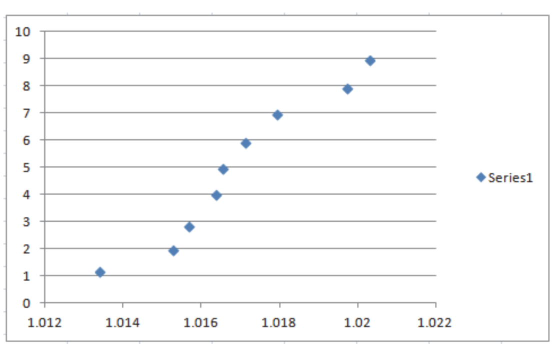
A **Paste Special** window will appear. Select **Values** and press **OK**.



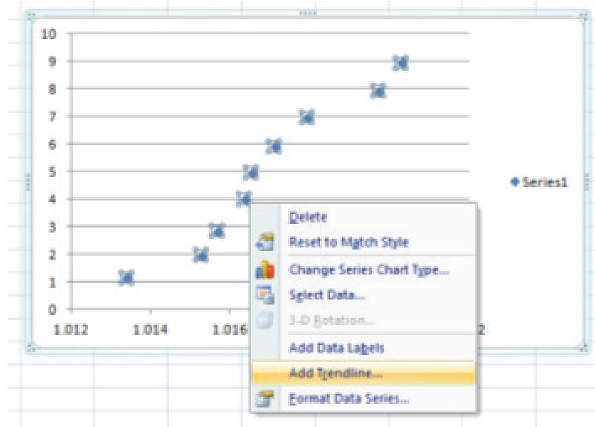
Plot the subset, selecting the corresponding depth values in columns F and G. In the **Insert** tab, select **Scatter with Only Markers** plot. The purpose of the G column is to switch which values are on the x and y axis for the plot.



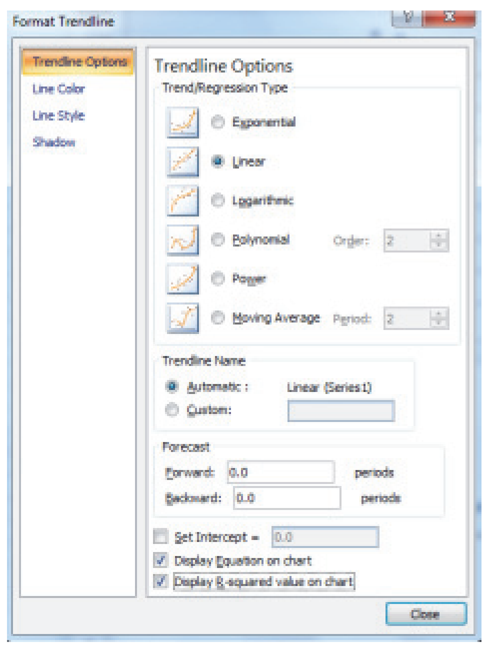
Please note that the algorithm values in the new plot are in the X-axis and the depth values are in the Y-axis. This is because the data is converted from algorithm values to the chart datum.



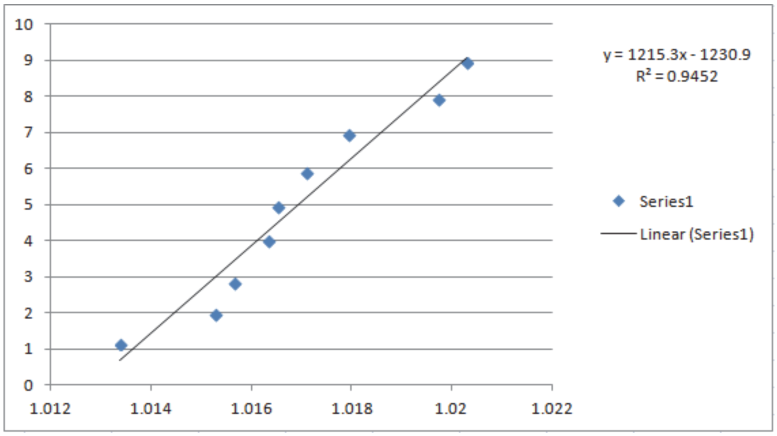
Right-click on the data points and select **Add Trendline**.



Make sure the regression type is linear. Check the **Display Equation on Chart** and **Display R-squared value on chart** boxes and press **Close**.

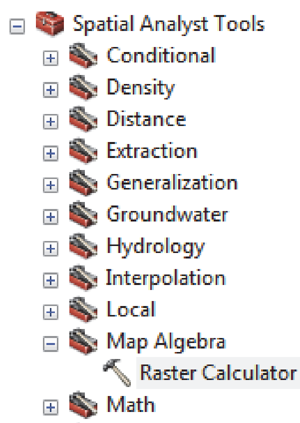


The resulting equation of the trend line is used for the referencing (in this example, the gain is 1215.3 and the offset is 1230.9).

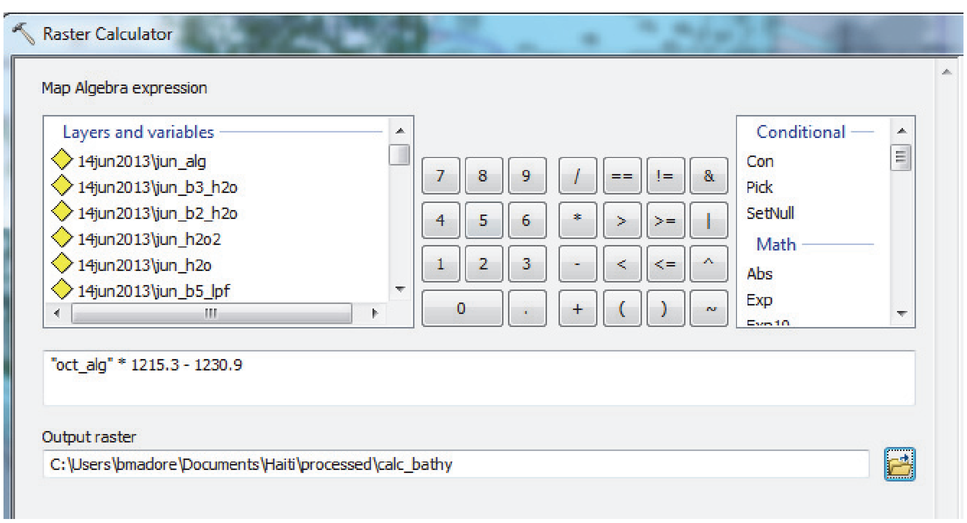


A.7.4 Applying the Gain and Offset (Referencing)

In ArcMap, select in the **ArcToolbox Spatial Analyst Tools / Map Algebra / Raster Calculator**.



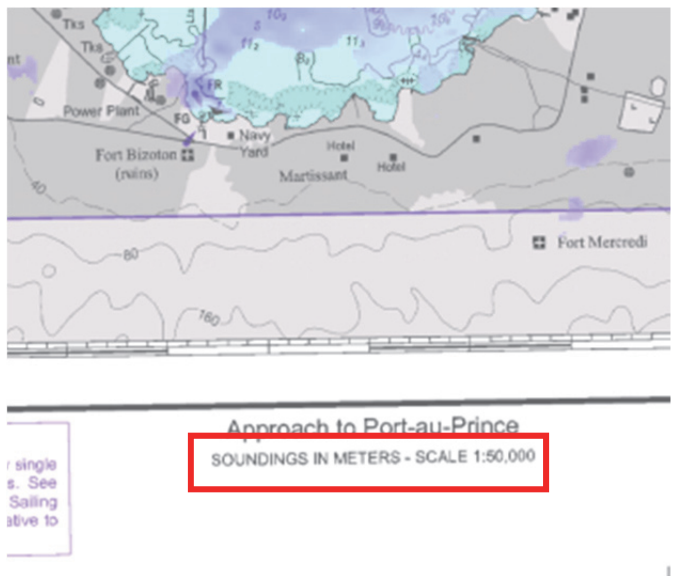
Select the algorithm layer and multiply the algorithm layer by the gain value from the excel sheet, and then subtract the b value. Save the file as "calc_bathy".



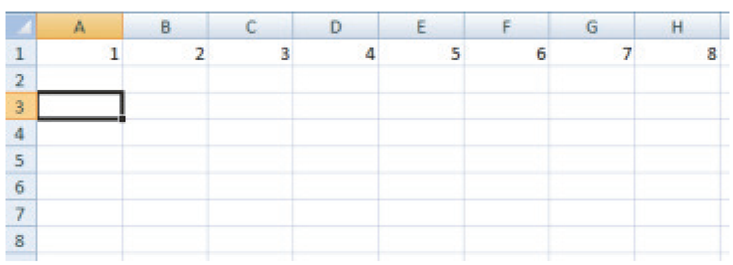
The "calc_bathy" file is the bathymetry referenced to the chart datum.

A.7.5 Raster Chart Referencing (Manual Referencing)

Identify the units of the soundings and the shallow areas the correlate with depth soundings. In this example, the soundings are in meters and the shallow areas are marked with light blue.

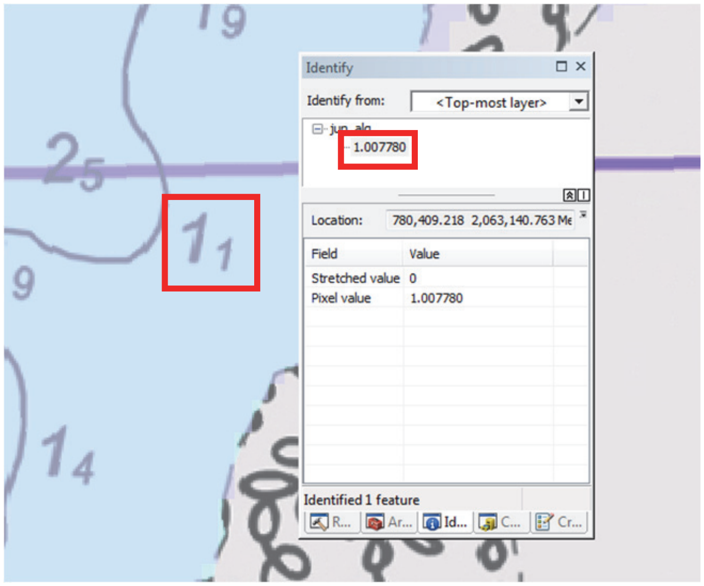


Open an MS Excel. Set up a row of values corresponding to the depth interval. For this data set the intervals are in 1 meter intervals.



Select the **Identify** tool.

Click on a sounding in the shallow area



Copy the bathymetry value to 4 decimal places (minimum) in the corresponding depth column in the excel table.

A	B	C	D
1	2	3	4
1.00778			

Sample more soundings over shallow areas. Make sure that you have at least 6 samples per depth value.

	A
1	1
2	1.1236
3	1.13119
4	1.1423
5	1.1046
6	1.116
7	1.1155
8	1.1088
9	1.1082

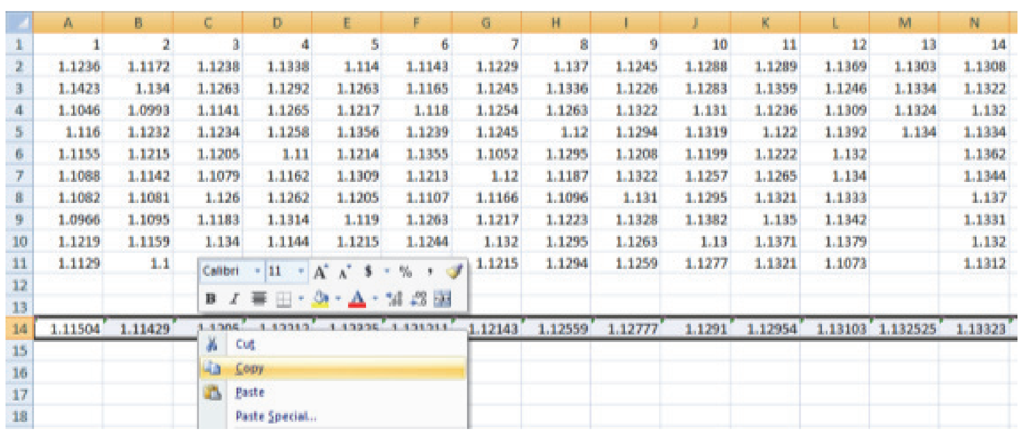
After you finish the shallow depth, proceed to find deeper depth values for the soundings over the deep algorithm results (in this case, over the dark blue areas). Typically 15 m is good in murky waters (e.g., north Atlantic waters) and 35 m in clear water (e.g., Caribbean waters).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17	20	22
2	1.1236	1.1172	1.1238	1.1338	1.114	1.1143	1.1229	1.137	1.1245	1.1288	1.1289	1.1369	1.1303	1.1308	1.1333	1.131	1.1368	1.1386
3	1.1423	1.134	1.1263	1.1292	1.1263	1.1165	1.1245	1.1336	1.1226	1.1283	1.1359	1.1246	1.1334	1.1322	1.1294	1.138	1.1367	1.1379
4	1.1046	1.0993	1.1141	1.1265	1.1217	1.118	1.1254	1.1263	1.1322	1.131	1.1236	1.1309	1.1324	1.132	1.1327	1.1321	1.1393	1.1358
5	1.116	1.1232	1.1234	1.1258	1.1356	1.1239	1.1245	1.12	1.1294	1.1319	1.122	1.1392	1.134	1.1334	1.1345	1.1381	1.1328	1.1345
6	1.1155	1.1215	1.1205	1.11	1.1214	1.1355	1.1052	1.1295	1.1208	1.1199	1.1222	1.132		1.1362	1.1359	1.1279	1.1327	1.1338
7	1.1088	1.1142	1.1079	1.1162	1.1309	1.1213	1.12	1.1187	1.1322	1.1257	1.1265	1.134		1.1344	1.139	1.1268	1.1302	1.1339
8	1.1082	1.1081	1.126	1.1262	1.1205	1.1107	1.1166	1.1096	1.131	1.1295	1.1321	1.1333		1.137	1.1355	1.1252	1.1336	1.1348
9	1.0966	1.1095	1.1183	1.1314	1.119	1.1263	1.1217	1.1223	1.1328	1.1382	1.135	1.1342		1.1331		1.1337	1.135	1.1357
10	1.1219	1.1159	1.134	1.1144	1.1215	1.1244	1.132	1.1295	1.1263	1.13	1.1371	1.1379		1.132		1.1338	1.139	
11	1.1129	1.1	1.1107	1.1077	1.1216		1.1215	1.1294	1.1259	1.1277	1.1321	1.1073		1.1312		1.1378		
12																		

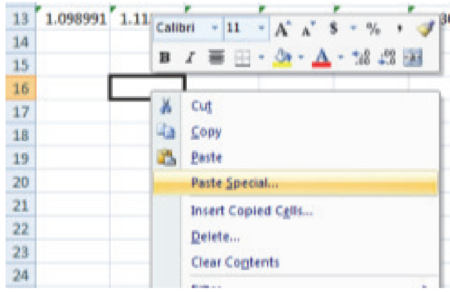
In column A, click on the cell that is two rows below the last value. Type "**=average(**" and mark the cells to average.

Repeat this average calculation for the other columns. Make sure that all the average values are in the same row.

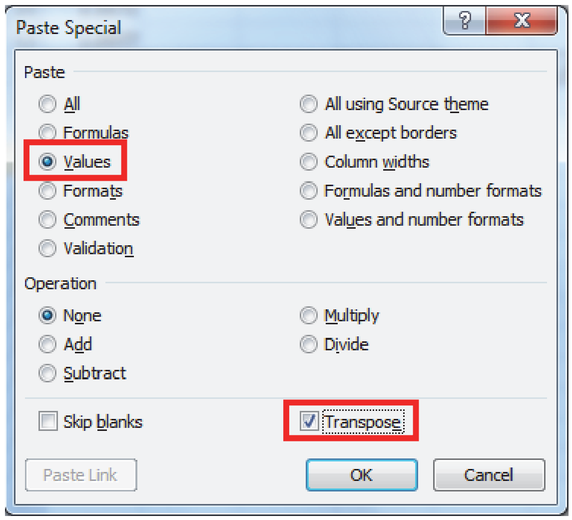
Select all the average values by left-clicking and marking them all. Right-click on the marked area and select **Copy**.



Select a data box that is below in **Column B** the data, right click and select **Paste Special**.



In the **Paste Special** window, select **Values**, and **Transpose**. Press **OK**.



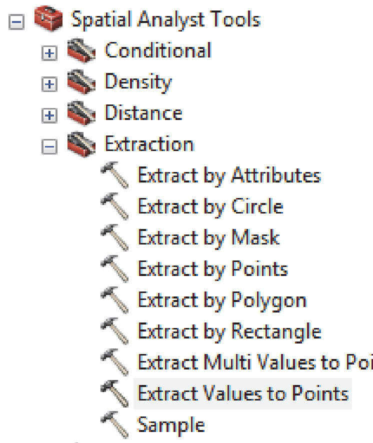
Continue as directed in sections A.7.3 and A.7.4.

A.8 Post Processing (Statistical Analysis)

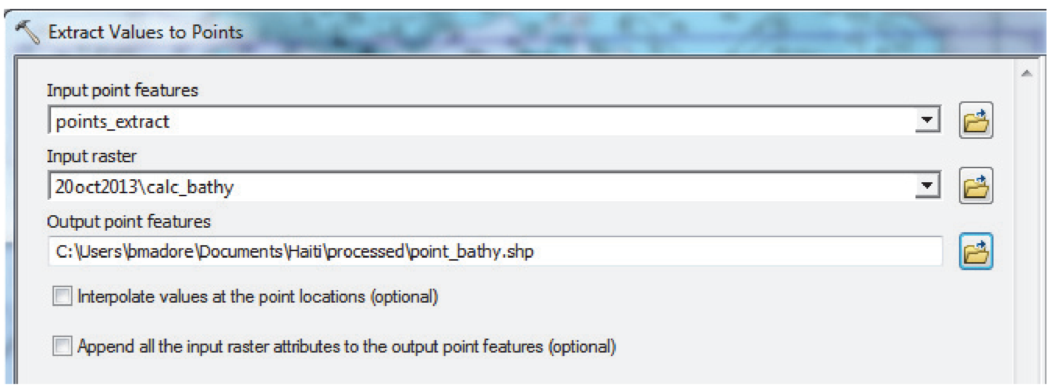
<u>**NOTE**</u>: Similar to the referencing step, the analysis can be conducted using either: 1) the S-57 attributes from an ENC, or 2) manually. It is recommended to use option 1 when possible, as it provides a fast and accurate solution. Otherwise, you will be required to generate point features file.

A.8.1 Statistical Analysis Using S-57 Attributes

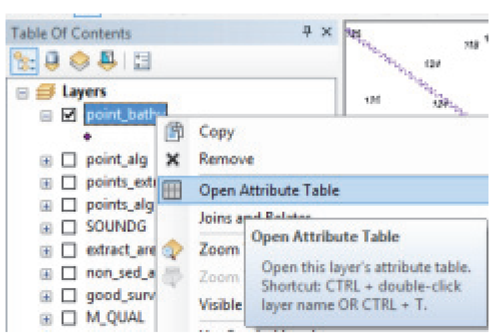
In the **ArcToolbox,** select **Spatial Analyst Tools / Extraction / Extract Values to Points**.



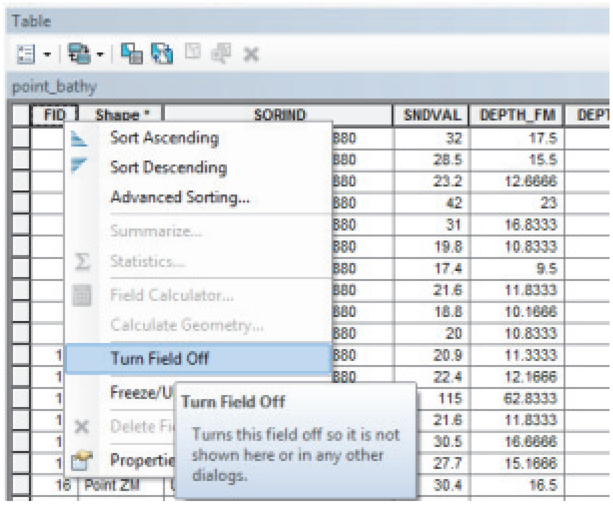
Use the files generated from the previous section (Section A.7). Use the “points_extract" feature as the **Input point features** and the "calc_bathy" layer as the **Input raster**. Save the file as "point_bathy.shp" and press **OK**.



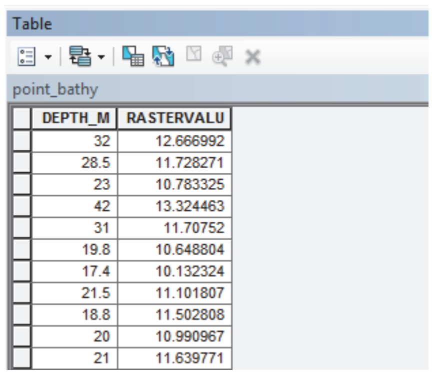
After the file has been generated, right-click on the "point_bathy" layer and select **Open Attribute Table.**



Apart from the DEPTH_M column and the RASTERVALU column, turn off the other layers by right-clicking on the name the name and selecting **Turn Field off**.

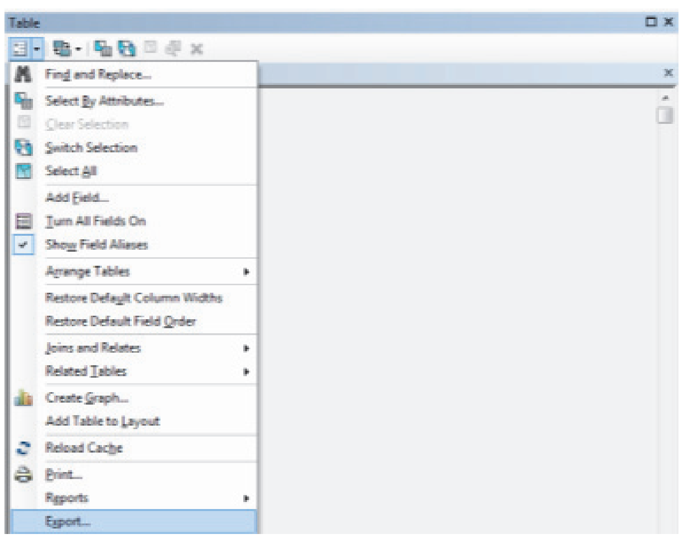


The table should contain only two fields.

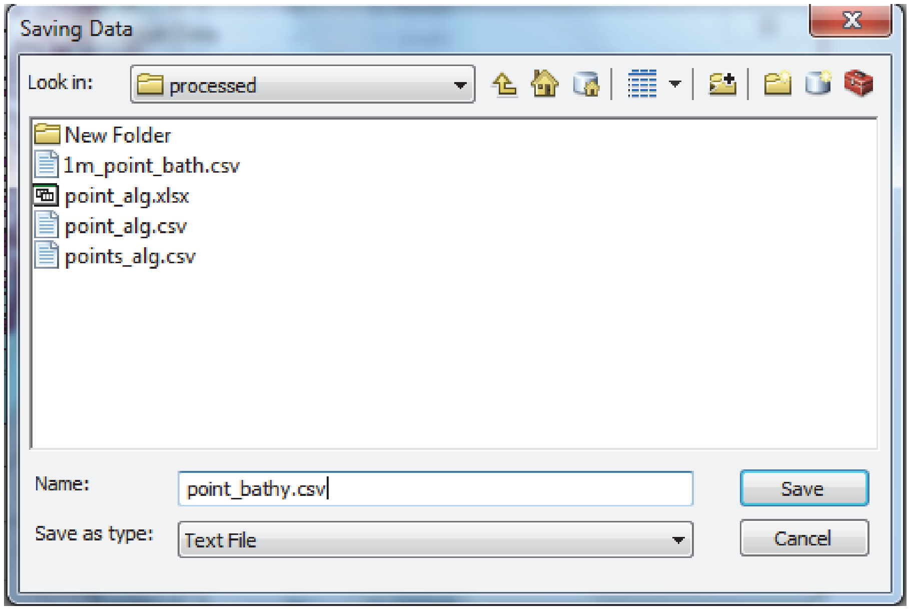


DEPTH_M	RASTERVALU
32	12.666992
28.5	11.728271
23	10.783325
42	13.324463
31	11.70752
19.8	10.648804
17.4	10.132324
21.5	11.101807
18.8	11.502808
20	10.990967
21	11.639771

Select **Table Options** and choose **Export.**

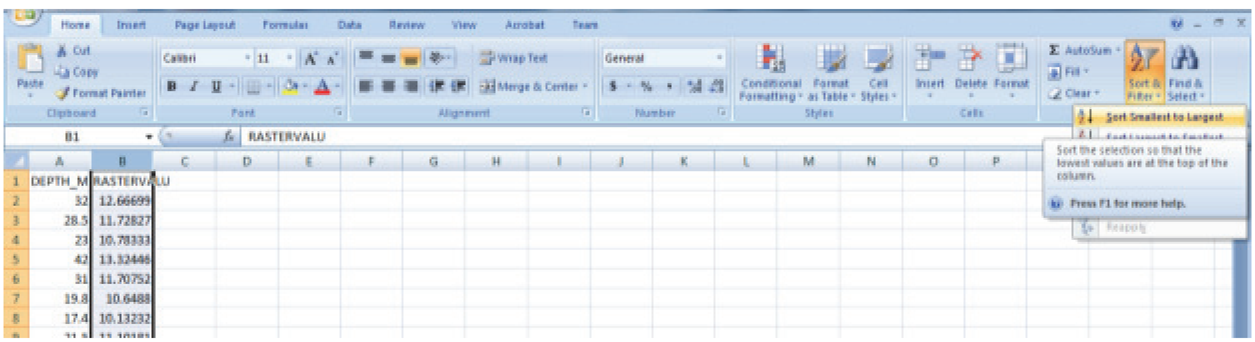


Select an output location to save the data and select **Text file** in the **Save as type**. Name the file "point_bathy.csv" (make sure to have the ***.csv** extension) and press **Save**.

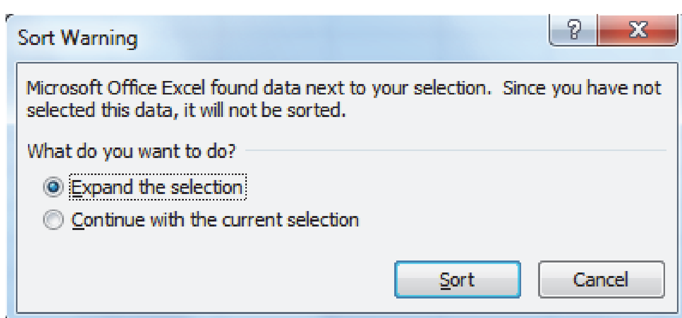


Select **No**, when it asks to add the new table to the current map.

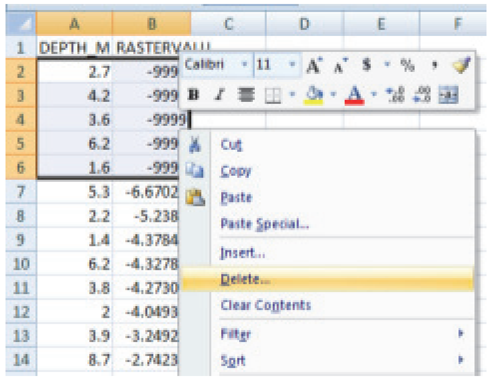
Open the "point_bathy.csv" file in excel and select the **RASTERVALU** column. In the **Home** tab select **Sort and Filter** tool and choose **Sort Smallest to Largest**.



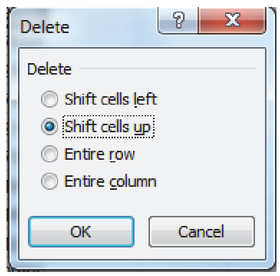
When the Sort Warning window appears, select **Expand the selection.**



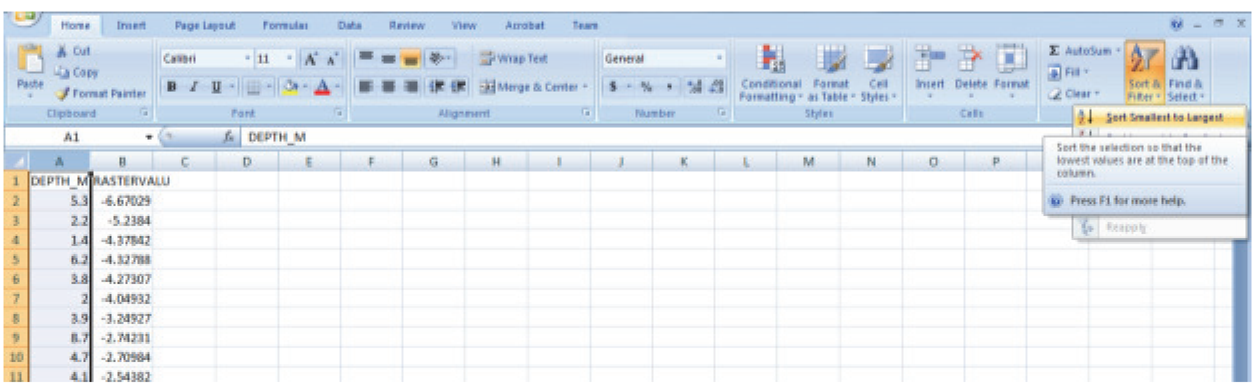
The lowest values in the RASTERVALU column will appear as -9999. These null values should be deleted. For each -9999, select both the A column value and the B column value then right-click and select **Delete.**



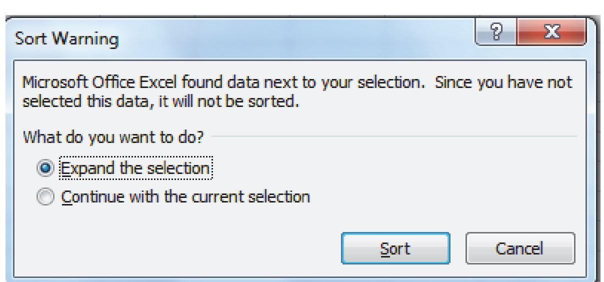
When the **Sort Warning** appears, select **Expand Selection**.



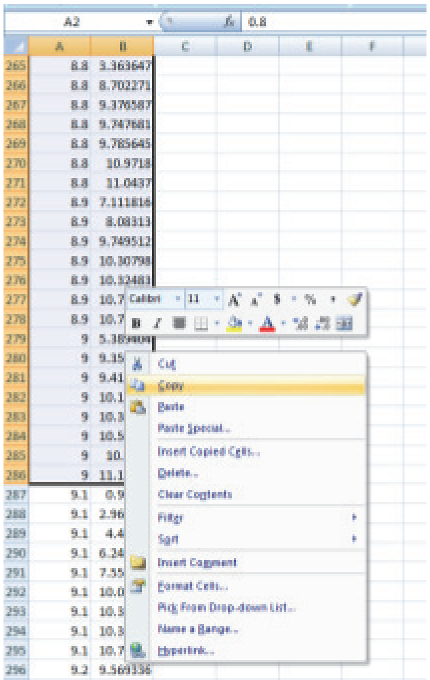
After removing the null values, the dataset will be sorted by depth. Select the DEPTH_M column and in the **Home** tab select **Sort and Filter** tool and choose **Sort Smallest to Largest**.

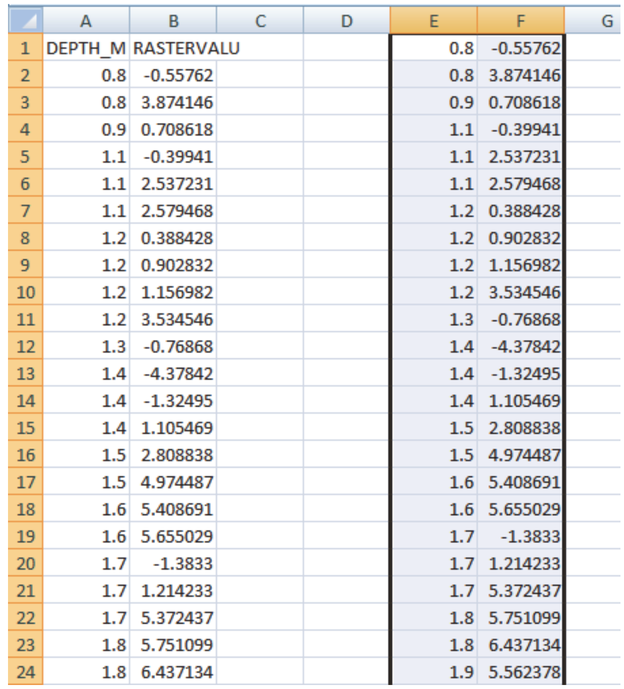


Select **Expand the Selection,** when the following warning appears.

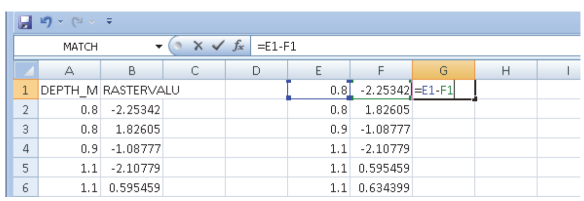


Based on the extinction depth determined when calculating the bathymetry in the previous section (9 meters for this example), select the values from the depth column and the corresponding column. Then copy/paste those values into column E and F.

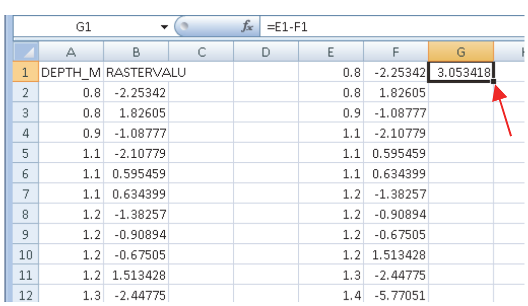


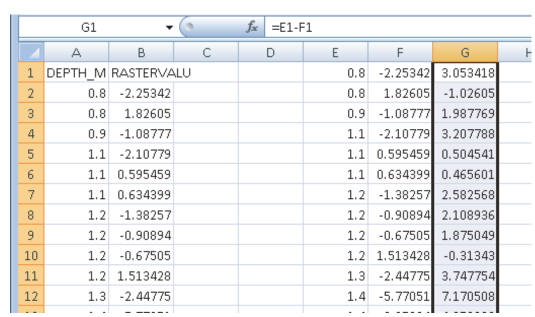


Next, the difference between the chart depth (column E) and the derived bathymetry values (column F) will be calculated. In cell G1, type "**=E1-F1**".



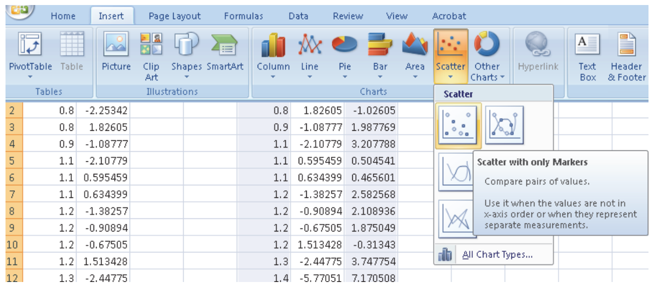
Select cell G1 and either drag the lower right corner until it reaches the bottom of the E and F column or double-click on the corner.



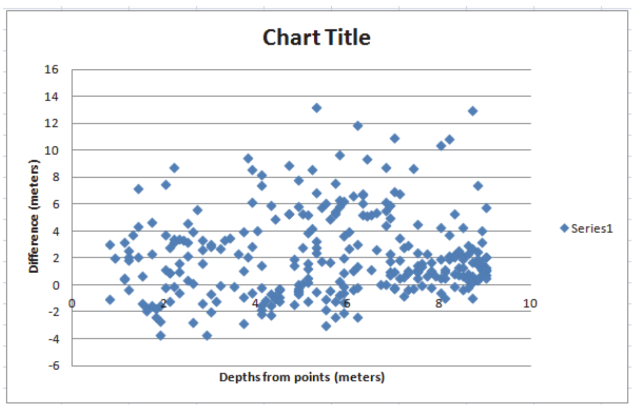


A.8.2 Scatter Plot

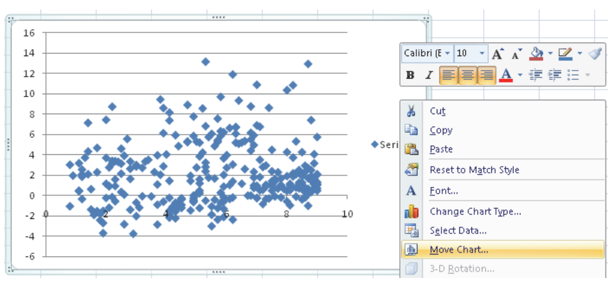
To create a scatter plot, first select column E, and while holding the **ctrl** key, select the G column as well. Then go to **Insert** tab and select **Scatter with only Markers**.



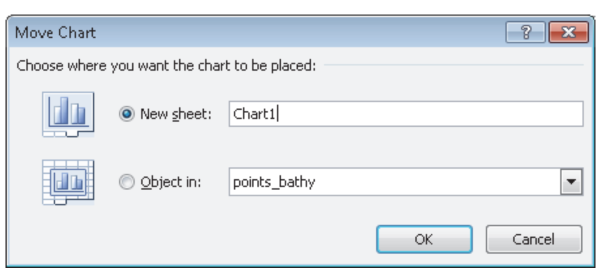
The resulting graph is a scatter plot of the difference between the derived bathymetry to the charted depth (Y-axis) as a function of depth (X-axis).



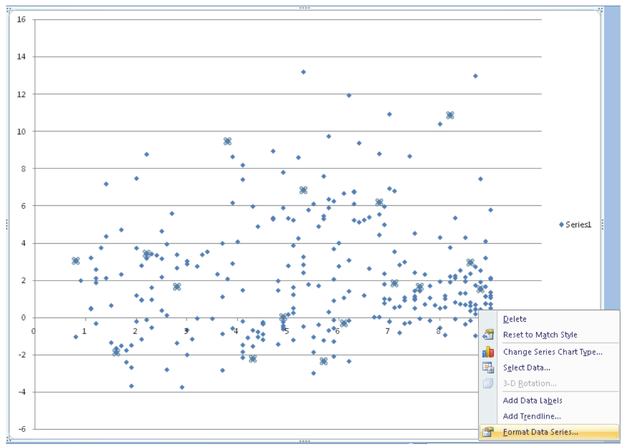
In order to observe a clearer plot, right click above the legend, and select **Move Chart..**.



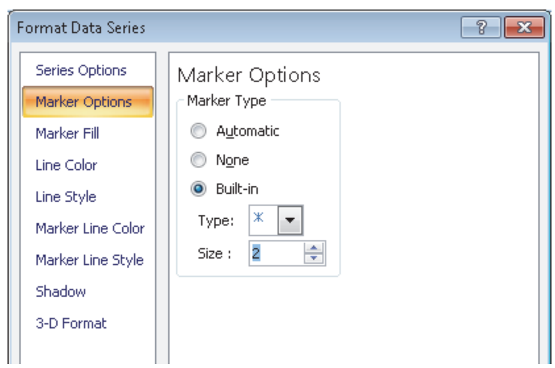
The **Move Chart** window will appear, select **New sheet** and press **OK**.



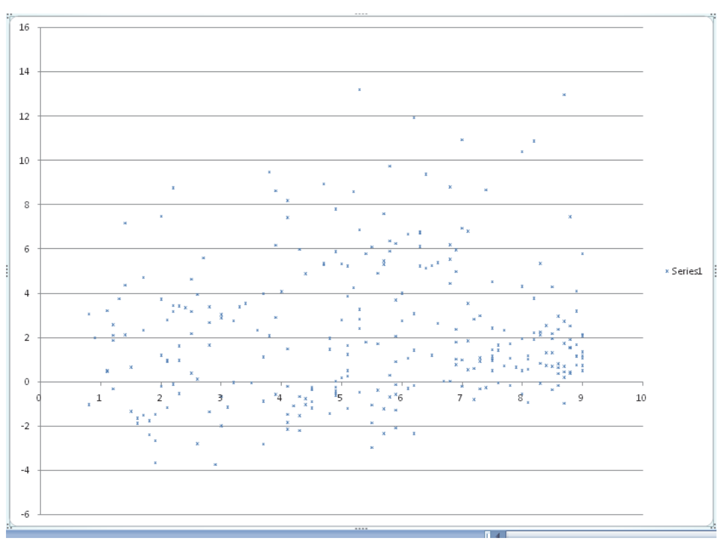
The scatter plot will now appear in a separate sheet will appear. Right-click on the data series, select **Format Data Series....**



In the **Marker Options** tab and select **Build-in** option with **Type: "*"** and **Size: "2"**. Press **Close**.



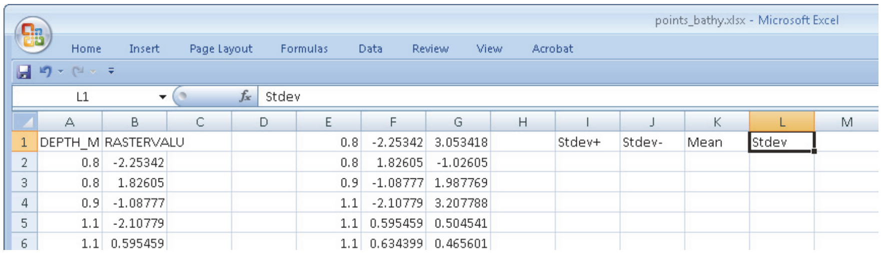
The plot now shows more clearly the distribution of the depth differences between the derived bathymetry and the charted depth.



<u>Note:</u> MS Excel provides more options for designing the scatter plot.

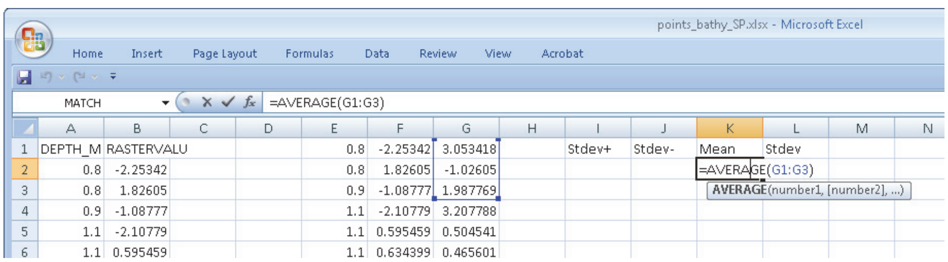
A.8.3 Mean and Standard Deviation

Type the following titles: "Stdev+" in cell I1, "Stdev-" in cell J1, "Mean" in cell K1, and "Stdev" in cell L1.



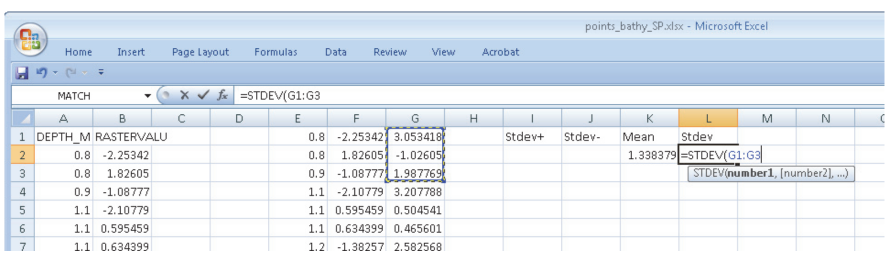
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	DEPTH_M	RASTERVALU			0.8	-2.25342	3.053418		Stdev+	Stdev-	Mean	Stdev	
2	0.8	-2.25342			0.8	1.82605	-1.02605						
3	0.8	1.82605			0.9	-1.08777	1.987769						
4	0.9	-1.08777			1.1	-2.10779	3.207788						
5	1.1	-2.10779			1.1	0.595459	0.504541						
6	1.1	0.595459			1.1	0.634399	0.465601						

In order to calculate the standard deviation and mean for each depth, they need to be binned. In space K2 type "**=AVERAGE(**" and then select and highlight in column B all values that are in depths that range between 0 m to 1 m according to column A.



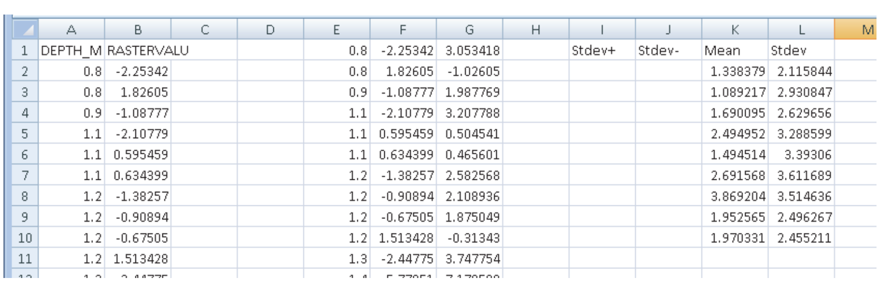
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	DEPTH_M	RASTERVALU			0.8	-2.25342	3.053418		Stdev+	Stdev-	Mean	Stdev		
2	0.8	-2.25342			0.8	1.82605	-1.02605				=AVERAGE(G1:G3)			
3	0.8	1.82605			0.9	-1.08777	1.987769							
4	0.9	-1.08777			1.1	-2.10779	3.207788							
5	1.1	-2.10779			1.1	0.595459	0.504541							
6	1.1	0.595459			1.1	0.634399	0.465601							

Similarly, in space L1 type "**=STDEV(**"and then select and highlight in column B all values that are in depths that range between 0.1 m to 1.0 m according to column A.



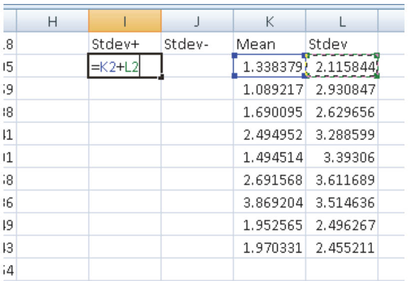
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	DEPTH_M	RASTERVALU			0.8	-2.25342	3.053418		Stdev+	Stdev-	Mean	Stdev		
2	0.8	-2.25342			0.8	1.82605	-1.02605				1.338379	=STDEV(G1:G3		
3	0.8	1.82605			0.9	-1.08777	1.987769							
4	0.9	-1.08777			1.1	-2.10779	3.207788							
5	1.1	-2.10779			1.1	0.595459	0.504541							
6	1.1	0.595459			1.1	0.634399	0.465601							
7	1.1	0.634399			1.2	-1.38257	2.582568							

Repeat the mean and standard deviation calculations for cells D2 and E2 for the depth ranges between 1.1 m to 2.0 m. and continue up to the extinction depth (9.0 m in this example). Type in column C the chart depth that correlates with the mean and the standard deviation (i.e., 1.0 m in cell C1, 2.0 m in cell C2, ...).

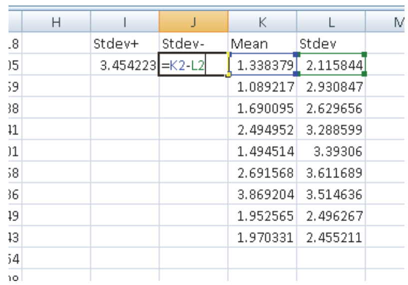


	A	B	C	D	E	F	G	H	I	J	K	L	M
1	DEPTH_M	RASTERVALU			0.8	-2.25342	3.053418		Stdev+	Stdev-	Mean	Stdev	
2	0.8	-2.25342			0.8	1.82605	-1.02605				1.338379	2.115844	
3	0.8	1.82605			0.9	-1.08777	1.987769				1.089217	2.930847	
4	0.9	-1.08777			1.1	-2.10779	3.207788				1.690095	2.629656	
5	1.1	-2.10779			1.1	0.595459	0.504541				2.494952	3.288599	
6	1.1	0.595459			1.1	0.634399	0.465601				1.494514	3.39306	
7	1.1	0.634399			1.2	-1.38257	2.582568				2.691568	3.611689	
8	1.2	-1.38257			1.2	-0.90894	2.108936				3.869204	3.514636	
9	1.2	-0.90894			1.2	-0.67505	1.875049				1.952565	2.496267	
10	1.2	-0.67505			1.2	1.513428	-0.31343				1.970331	2.455211	
11	1.2	1.513428			1.3	-2.44775	3.747754						

In order to plot the standard deviations with the mean, the standard deviation will be added and subtracted from the mean. Type "**=K2 + L2**" in cell I2. Similarly, type "**=K2 - L2**" in cell J1.

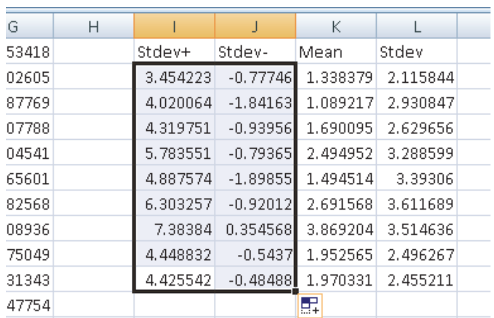


	H	I	J	K	L
.8		Stdev+	Stdev-	Mean	Stdev
5		=K2+L2		1.338379	2.115844
9				1.089217	2.930847
8				1.690095	2.629656
1				2.494952	3.288599
1				1.494514	3.39306
8				2.691568	3.611689
6				3.869204	3.514636
9				1.952565	2.496267
3				1.970331	2.455211
4					



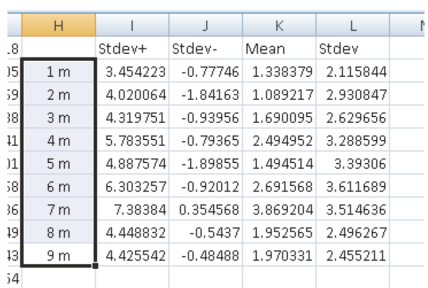
	H	I	J	K	L	M
.8		Stdev+	Stdev-	Mean	Stdev	
5		3.454223	=K2-L2	1.338379	2.115844	
9				1.089217	2.930847	
8				1.690095	2.629656	
1				2.494952	3.288599	
1				1.494514	3.39306	
8				2.691568	3.611689	
6				3.869204	3.514636	
9				1.952565	2.496267	
3				1.970331	2.455211	
4						

Repeat the step above for the rest of the cells.



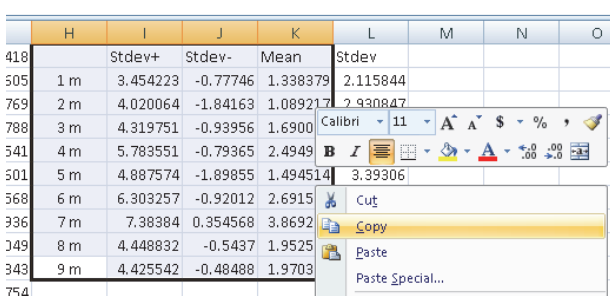
G	H	I	J	K	L
53418		Stdev+	Stdev-	Mean	Stdev
02605		3.454223	-0.77746	1.338379	2.115844
87769		4.020064	-1.84163	1.089217	2.930847
07788		4.319751	-0.93956	1.690095	2.629656
04541		5.783551	-0.79365	2.494952	3.288599
65601		4.887574	-1.89855	1.494514	3.39306
82568		6.303257	-0.92012	2.691568	3.611689
08936		7.38384	0.354568	3.869204	3.514636
75049		4.448832	-0.5437	1.952565	2.496267
31343		4.425542	-0.48488	1.970331	2.455211
47754					

In column H write the chart depths that were extracted (this example went from 1 to 9 meters).



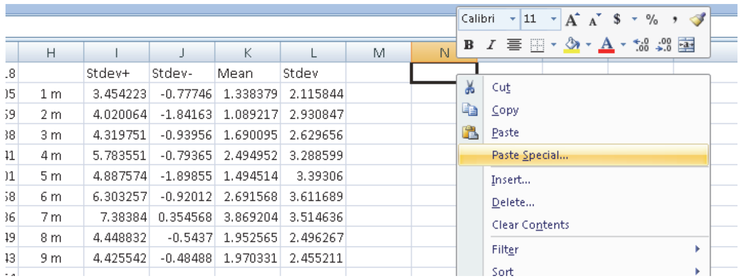
	H	I	J	K	L
.8		Stdev+	Stdev-	Mean	Stdev
5	1 m	3.454223	-0.77746	1.338379	2.115844
9	2 m	4.020064	-1.84163	1.089217	2.930847
8	3 m	4.319751	-0.93956	1.690095	2.629656
1	4 m	5.783551	-0.79365	2.494952	3.288599
1	5 m	4.887574	-1.89855	1.494514	3.39306
8	6 m	6.303257	-0.92012	2.691568	3.611689
6	7 m	7.38384	0.354568	3.869204	3.514636
9	8 m	4.448832	-0.5437	1.952565	2.496267
3	9 m	4.425542	-0.48488	1.970331	2.455211
4					

Select the data in columns H to K, right click and select **Copy**.



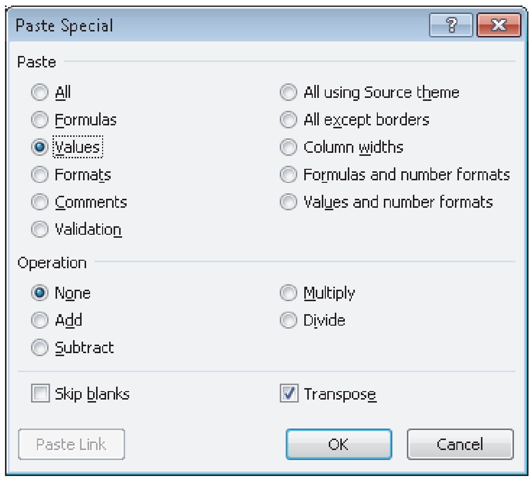
	H	I	J	K	L
418		Stdev+	Stdev-	Mean	Stdev
505	1 m	3.454223	-0.77746	1.338379	2.115844
769	2 m	4.020064	-1.84163	1.089217	2.930847
788	3 m	4.319751	-0.93956	1.6900	
541	4 m	5.783551	-0.79365	2.4949	
501	5 m	4.887574	-1.89855	1.494514	3.39306
568	6 m	6.303257	-0.92012	2.6915	
936	7 m	7.38384	0.354568	3.8692	
049	8 m	4.448832	-0.5437	1.9525	
343	9 m	4.425542	-0.48488	1.9703	

Right-click on cell N1 and select **Paste Special...**.

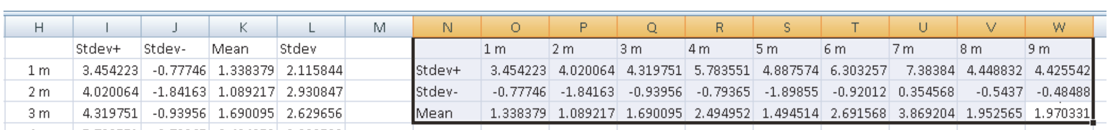


H	I	J	K	L	M	N
	Stdev+	Stdev-	Mean	Stdev		
1 m	3.454223	-0.77746	1.338379	2.115844		
2 m	4.020064	-1.84163	1.089217	2.930847		
3 m	4.319751	-0.93956	1.690095	2.629656		
4 m	5.783551	-0.79365	2.494952	3.288599		
5 m	4.887574	-1.89855	1.494514	3.39306		
6 m	6.303257	-0.92012	2.691568	3.611689		
7 m	7.38384	0.354568	3.869204	3.514636		
8 m	4.448832	-0.5437	1.952565	2.496267		
9 m	4.425542	-0.48488	1.970331	2.455211		

Select **Values** and **Transpose** and press **OK**.

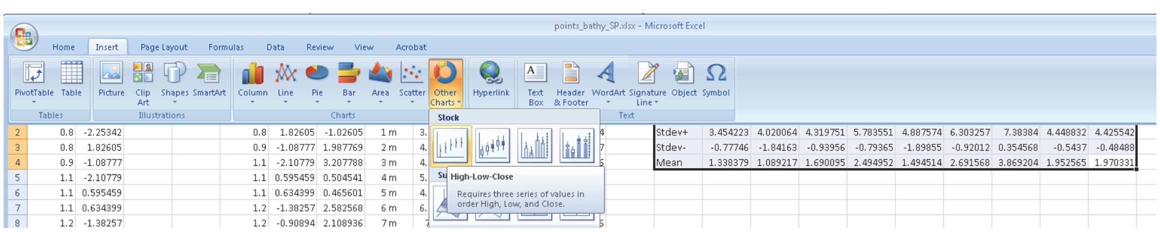


The dataset will look as follows:

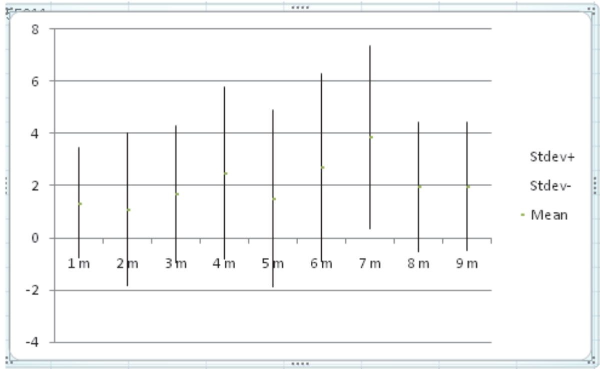


H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
	Stdev+	Stdev-	Mean	Stdev			1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m
1 m	3.454223	-0.77746	1.338379	2.115844		Stdev+	3.454223	4.020064	4.319751	5.783551	4.887574	6.303257	7.38384	4.448832	4.425542
2 m	4.020064	-1.84163	1.089217	2.930847		Stdev-	-0.77746	-1.84163	-0.93956	-0.79365	-1.89855	-0.92012	0.354568	-0.5437	-0.48488
3 m	4.319751	-0.93956	1.690095	2.629656		Mean	1.338379	1.089217	1.690095	2.494952	1.494514	2.691568	3.869204	1.952565	1.970331

Select the new dataset and go to **Insert** tab and select **Other Charts/Stock/High-Low-Close**.



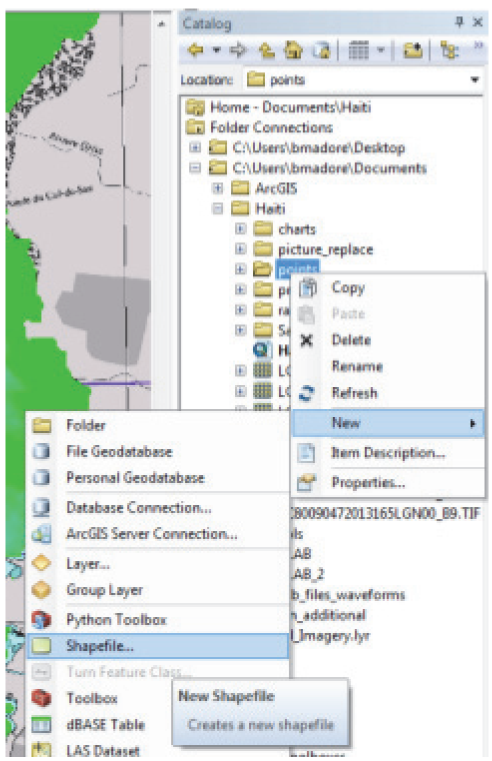
The resulting graph will appear as the following:



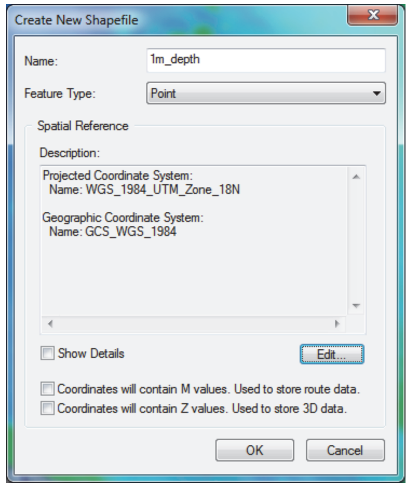
A.8.4 Manual Sampling

In case the S-57 attribute files are not available, it is possible to create a point shapefile manually.

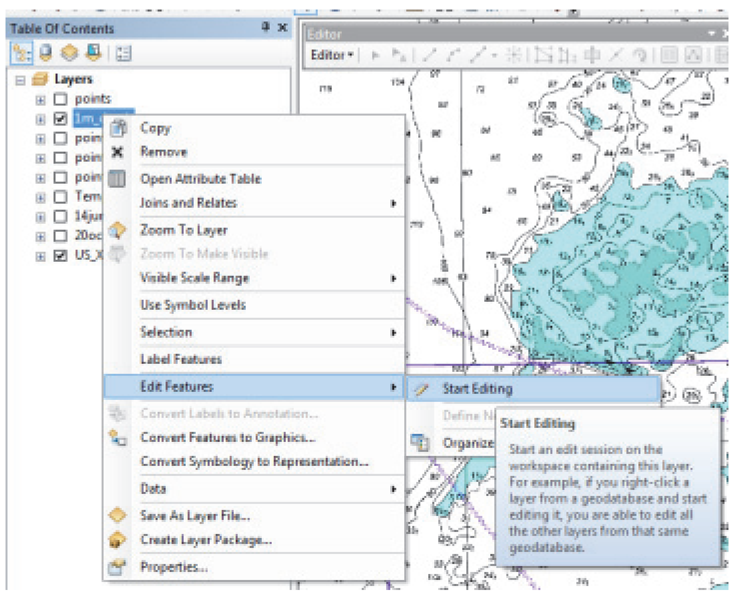
Open the **Catalog** and navigate to the folder to save the point feature. Right-click the folder and select **New** then **Shapefile**.



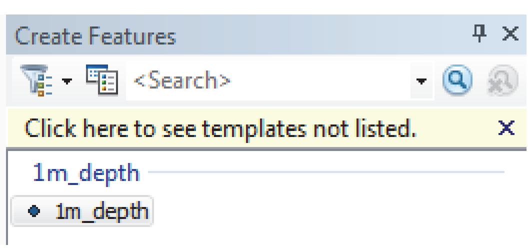
Enter the name of the point feature (the first point file will be 1m) and select **edit** to choose the coordinate system of the area. Select **OK.**



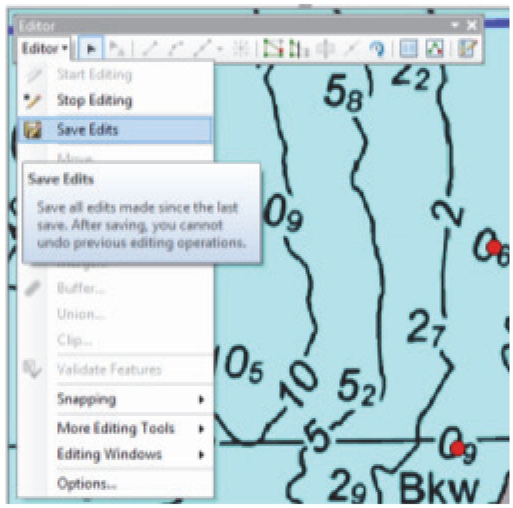
Right-click the shapefile and select **Edit features** then **start editing**. If a warning pops up select continue.



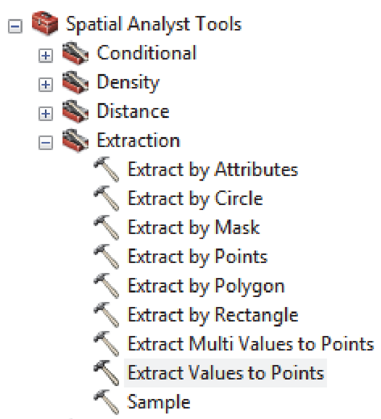
Open the **Create Features** tool and select the 1m_depth feature.



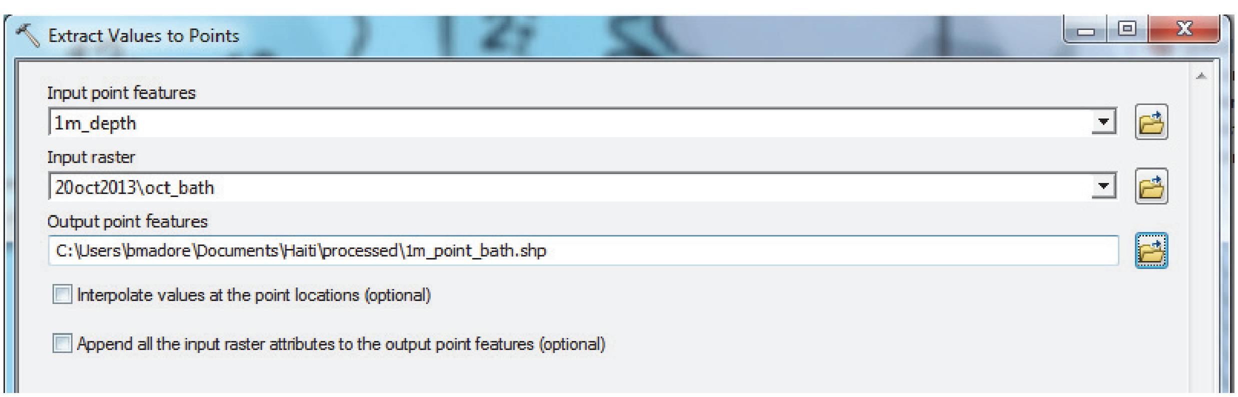
Using the chart as a reference, click on each depth value of 1 meter (i.e., between 0.1 to 1.0 m). For example below sounding at 0.6 m and 0.9 m were marked. Try to select at least 6 soundings. Once finished, select **Save Edits** followed by **Stop Edits** in the **Editor toolbar.**



In **ArcToolbox,** select **Spatial Analyst Tools / Extraction / Extract Values to Points**.

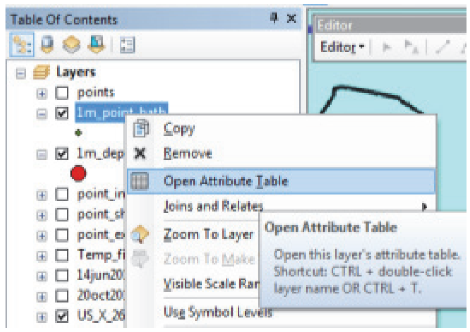


Input "1m_depth" as the **input point feature** and the "calc_bathy" layer as the **Input raster**. Select a destination to save the output file, name the file "1m_point_bath" and press **OK**.

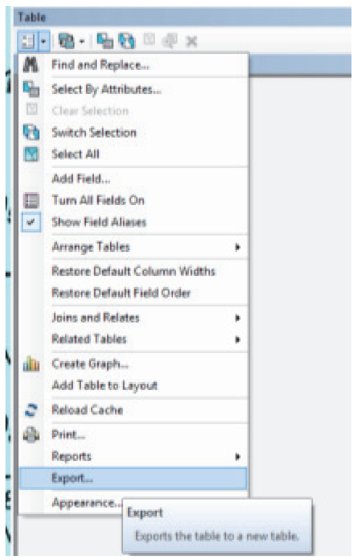


Repeat all the steps in this section for the other depth ranges.

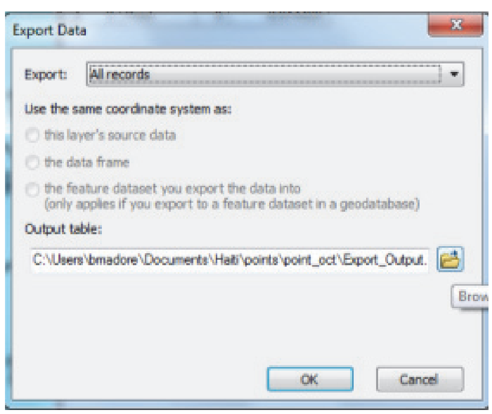
After sampling sounding for the depths up to the extinction depth, Right-click on the "1m_point_bath" layer in the **Table of Contents** and select **Open attribute table**.



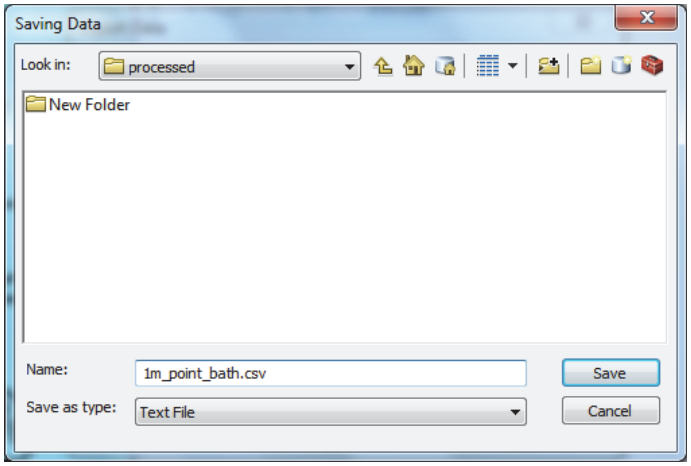
In the table options, select **export.**



Make sure to export **All records** and select the folder icon.



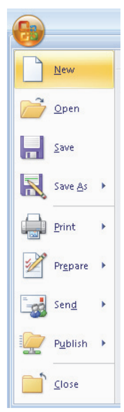
Navigate to the data folder to save the file to and switch the **Save as type** to **text file.** Save the file as "1m_point_bath.csv" (make sure to save the file as *.csv) and press **Save**.



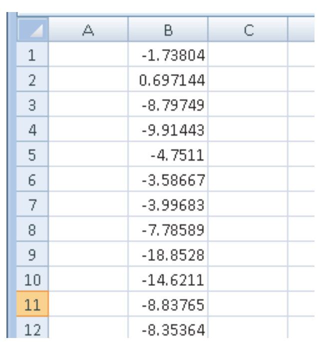
When prompted to add the new table to the current map, select **No**.

Repeat the export process for the rest of the depth layers created.

Open all the new *.csv files n MS Excel. Also, a new blank sheet



Copy the RASTERVALU from "1m_point_bath.csv" into column B the blank sheet.



	A	B	C
1		-1.73804	
2		0.697144	
3		-8.79749	
4		-9.91443	
5		-4.7511	
6		-3.58667	
7		-3.99683	
8		-7.78589	
9		-18.8528	
10		-14.6211	
11		-8.83765	
12		-8.35364	

Type the number "1" in column A for all the depth values in column B.

	A	B	C
1	1	-1.73804	
2	1	0.697144	
3	1	-8.79749	
4	1	-9.91443	
5	1	-4.7511	
6	1	-3.58667	
7	1	-3.99683	
8	1	-7.78589	
9	1	-18.8528	
10	1	-14.6211	
11	1	-8.83765	
12	1	-8.35364	
[illegible]	1	[illegible]	

Repeat these steps for the other water depths as follows:

	A	B	C	D
25	1	-8.25415		
26	1	-16.5034		
27	1	5.460571		
28	1	-1.23267		
29	1	2.885376		
30	1	4.381714		
31	1	6.727783		
32	1	7.282349		
33	1	-8.51575		
34	1	0.795654		
35	2	2.495117		
36	2	-8.42615		
37	2	-6.50061		
38	2	1.09436		
39	2	0.447754		
40	2	1.650024		
41	2	-3.59827		
42	2	-1.72559		
43	2	-16.4685		

After finishing, compile all the sampled data into one sheet. Save the file.

Go to section A.8.2 and A.8.3 for analyzing the derived bathymetry results.

Note: In order to avoid operator confusion during the sampling procedure, each depth range has an integer value.

APPENDIX B. ABBREVATIONS AND ACROYNMS

DEM - Digital Elevation Model
ECDIS - Electronic Chart and Display Information Systems (ECDIS)
ENC - Electronic Navigation Chart
GIS - Geographic Information System
IHO - International Hydrographic Organization
JHC - Joint Hydrographic Center
LAT - Lowest Astronomical Tide
MACHC - Meso American and Caribbean Sea Hydrographic Commission
MCD - Marine Chart Division
MLLW - Mean Lower Low Water
NASA - National Aeronautics and Space Administration
NGA - National Geospatial-Intelligence Agency
NITF - National Imagery Transmission Format
NIR - Near Infrared
NOAA - National Oceanic and Atmospheric Administration
OCS - Office of Coast Survey
OLI - Operational Land Imager
SDB - Satellite-derived bathymetry
SHOH - Service Hydrographique et Océanographique de Haiti
USGS - U.S. Geological Survey
WV-2 - WorldView 2